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ON

## TUBULAR GIRDER BRIDGES.

BY

WILLIAM FAIRBAIRN, M. INST. C.E.

WITH AN ABSTRACT OF THE DISCUSSION UPON THE PAPER.

**EDITED BY**

CHARLES MANBY, M. INST. C.E.,

**SECRETARY.**

EXCERPT MINUTES OF PROCEEDINGS, VOL. IX.

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## INSTITUTION OF CIVIL ENGINEERS.

March 12, 1850.

WILLIAM CUBITT, President, in the Chair.

No. 826.—“On Tubular Girder Bridges.”\*

By William Fairbairn, M. Inst. C. E.

**DOUBTS** having been entertained as to the ultimate security of the **Torksey Bridge**, over the **River Trent**, the Author has investigated the subject with the utmost care and attention.

A difference of opinion appears to exist,—

1st. As to the application of a given formula† for computing the strength of wrought-iron tubular girders.

2ndly. As to the excess of strength that should be given to a tubular-girder bridge, over the greatest load that can be brought upon it; and,

3rdly. As to the effects of impact, and the best mode of testing the strength, and proving the security, of the bridge.

These appear to be the chief points at issue: and, as a reply to both parties by whom he has been consulted, the Author has endeavoured to enunciate such views as will, he trusts, settle the question, and prove satisfactory as to the strength and other properties of these important structures. Previous to entering upon the investigation, it may, however, be requisite to offer a few remarks relative to the construction, and other matters connected with the permanency and security of this description of bridge.

\* The discussion on this paper extended over portions of several evenings, at different periods, but the abstract of the whole is given consecutively.

† Vide page 5.

#### LAB GIRDER BRIDGES.

g for its object public convenience a roughfare, should possess within its security. Bridges and viaducts elements, as they are peculiarly whatever cause such accident may arise, are interested in the strength and

In the introduction of a new system the use of a new and comparatively small projector, on public grounds, to be minute circumstance directly, or indirectly, the bridge. In those of the tubular of this kind are of primary importance upon the principle of construction material employed and of the workmanship every case should be of the very best

of tubular-girder bridges, the Author uses principles; and having a superiority in strength, durability, and in spans, he has not hesitated to adopt. However, becomes necessary, from a rigid examination, and before roughfares, it is essential to subject tests. These tests and examinations, and it may safely be affirmed, that bridges have been duly proportioned. The least reason to doubt their tubular-girder bridge originated in arches, and during their first application utmost precaution was observed of the several parts. These experiments made at Millwall, tubular Bridge; and, after repeated, the resisting powers and other things were fully established. From this is deduced, for calculating the span of bridge, from 30 feet up to 100 feet, and as that formula is now believed it may be relied upon as perfect, ever, from anything like ambiguity, certain points which should be taken into consideration.

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balance the two resisting forces of tension and compression in a wrought-iron tubular girder, having a cellular top, that the sectional area of the bottom should be to the sectional area of the top, as 11 to 12; which being the correct relative proportion of those parts, it then follows, that by any increase to the one, without a proportionate addition to the other, the bridge will be rendered weaker; inasmuch, as increased weight is given to the girder by the introduction of a useless quantity of material, which, in this instance, is totally unproductive. This being the case, it is of importance to preserve, as nearly as possible, the correct relative proportion of the parts, in order to ensure the maximum of strength in the two resisting forces of tension and compression—an arrangement essentially important in these structures, and also in the application of the formula to determine the ultimate strength of the girder. If, for example, an excess of material was given to the bottom of a girder, the formula,  $W = \frac{a d c}{l}$ , would not apply, as the top and

bottom areas would be disproportionate to each other, and that in excess would have to be reduced to the due proportion of 11 to 12; or, in other words, the additional strength must be omitted from the calculation, in computing the strength of the bridge. The same reasoning will apply, where the excess of area happens to be in the cellular top, although in this case the formula,  $W = \frac{a d c}{l}$ , still applies, as the excess cannot be considered in the calculation of the strength of the girder.

Assuming, however, that these proportions are maintained, the above formula furnishes a correct principle, on which to estimate the strength of wrought-iron tubes of this description, whatever may be their depths, or their relative dimensions.\*

In the case of the Torksey Tubular Bridge, of 130 feet clear span,

\* Mr. Tate, an eminent mathematician, remarks upon the formula—

1st. With respect to  $W = \frac{a d c}{l}$ , where  $a$  is the area of the section of the bottom, and  $c = 80$ , the constant deduced on this supposition, will apply to all depths of the tube, within short limits of error, where such depths, or  $a$  are large in proportion to the depth of the cells, and the thickness of the plates.

2nd. With respect to the formula  $W = \frac{a d c}{l}$ , when  $a$  is the area of the whole section, and  $c = 26.7$ , then the tubes should be similar in all respects, but a slight variation in depth, from that of similar form, will not produce much error, especially where the depth is considerable. At the same time it must be observed, that both formulæ apply with great exactness, where the tubes are similar.

Every structure having for its object public convenience and the support of a public thoroughfare, should possess within itself the elements of undeniable security. Bridges and viaducts should especially contain those elements, as they are peculiarly liable to accident; and from whatever cause such accident may arise, the community must be equally interested in the strength and durability of the structure. In the introduction of a new system of construction, comprising the use of a new and comparatively untried material, it behoves the projector, on public grounds, to be careful and attentive to the most minute circumstance directly, or indirectly affecting the security of the bridge. In those of the tubular construction, considerations of this kind are of primary importance, as much depends, not only upon the principle of construction, but upon the quality of the material employed and of the workmanship introduced, which in every case should be of the very best description.

In the construction of tubular-girder bridges, the Author has endeavoured to apply these principles; and having a strong conviction of their great superiority in strength, durability, and cheapness, for traversing large spans, he has not hesitated to advocate their introduction. It, however, becomes necessary, from time to time, to submit them to a rigid examination, and before opening such bridges as public thoroughfares, it is essential to subject them to severe and satisfactory tests. These tests and examinations have been various and frequent, and it may safely be affirmed, that in no case, where tubular-girder bridges have been duly proportioned and well executed, has there been the least reason to doubt their security.

The first idea of a tubular-girder bridge originated in a long series of experimental researches, and during their first application to railway constructions, the utmost precaution was observed in the due and perfect proportion of the several parts. These proportions were deduced from the experiments made at Millwall, upon the model of the Britannia Tubular Bridge; and, after repeated tests upon a large scale (full size), the resisting powers and other properties of this kind of bridge were fully established. From these experiments a formula was deduced, for calculating the ultimate strength of every description of bridge, from 30 feet up to 300 feet, or even to 1000 feet span; and as that formula is now before the public, it is believed, that it may be relied upon as perfectly accurate. To relieve it, however, from anything like ambiguity, it will be well to state, briefly, certain points which should be taken into consideration in its application.

It has already been determined by experiment, that in order to

balance the two resisting forces of tension and compression in a wrought-iron tubular girder, having a cellular top, that the sectional area of the bottom should be to the sectional area of the top, as 11 to 12; which being the correct relative proportion of those parts, it then follows, that by any increase to the one, without a proportionate addition to the other, the bridge will be rendered weaker; inasmuch, as increased weight is given to the girder by the introduction of a useless quantity of material, which, in this instance, is totally unproductive. This being the case, it is of importance to preserve, as nearly as possible, the correct relative proportion of the parts, in order to ensure the maximum of strength in the two resisting forces of tension and compression—an arrangement essentially important in these structures, and also in the application of the formula to determine the ultimate strength of the girder. If, for example, an excess of material was given to the bottom of a girder, the formula,  $W = \frac{a d c}{l}$ , would not apply, as the top and bottom areas would be disproportionate to each other, and that in excess would have to be reduced to the due proportion of 11 to 12; or, in other words, the additional strength must be omitted from the calculation, in computing the strength of the bridge. The same reasoning will apply, where the excess of area happens to be in the cellular top, although in this case the formula,  $W = \frac{a d c}{l}$ , still applies, as the excess cannot be considered in the calculation of the strength of the girder.

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# ULAR GIRDER BRIDGES.

dimensions of the girders in the mic  
Plate 11):—

## CTIONAL AREA OF THE TOP.

	Ft.	In.	In.	In.	In.
lates . . .	2	8 $\frac{1}{2}$	$\times$ 2	$\times$ $\frac{3}{8}$	= 24.47
. . . . .	1	1 $\frac{1}{2}$	$\times$ 3	$\times$ $\frac{5}{16}$	= 12.42
. . . . .	0	4 $\frac{3}{4}$	$\times$ 9	$\times$ $\frac{1}{16}$	= 13.35

ur top as given by Mr. Fowler . . . . .	50.24
by Capt. Simmons . . . . .	51.72

Mean . . . . . 50.98

## CTIONAL AREA OF THE BOTTOM.

	Ft.	In.	In.	In.	In.
plates . . .	2	9	$\times$ 2	$\times$ $\frac{3}{8}$	= 41.25
. . . . .	1	0	$\times$ $\frac{3}{4}$		= 9.00
. . . . .	0	3 $\frac{3}{4}$	$\times$ 2	$\times$ $\frac{1}{16}$	= 4.68

Area of the bottom . . . . . 54.93

evident want of proportion, the bottom  
the top, which renders a reduction of t  
e girder from 54.93 to 46.76 absolute:  
formula,  $W = \frac{a d c}{l}$ , or,  $\frac{46.76 \times 120}{1560}$

ons the breaking weight in the middle.  
4=1152 tons, as the breaking weight,  
of the spans of the Torksey Bridge, ne  
rs, ballast, rails, chairs, &c., which are di  
t be deducted from the breaking weigh

nates an equal distribution of the load  
a span of 130 feet, as follows:—

	Tons.	Tons.
chairs . . . . .	8	} = 177
atform . . . . .	15	
e beams . . . . .	27	
inches thick . . . . .	35	
weight of the four girders, re each 46 tons in weight (it have been the whole weight qually distributed) . . . . .	92	} = 195
ust be added the rolling load, as pon between Mr. Fowler and Capt. s . . . . .		

Total load . . . . . 372

middle, as

Now as the ultimate strength of the bridge is 1152 tons, it follows, that 177 being a constant will reduce its bearing powers to  $1152 - 177 = 975$  tons, as a resisting force to the heaviest rolling load that can be brought upon the bridge, being in the ratio of 975 to 195, or 5 to 1.\* These appear to be the facts of the case; and although the principal girders do not attain the standard of strength which the Author has ventured to recommend, as the limit of force; they are, nevertheless, sufficiently strong to render the bridge perfectly secure. In the calculations for estimating the strength of bridges of this description, it is always assumed, that the proportions of the top and bottom of the girder are not only correct, but that the sides are sufficiently rigid to retain the girder in shape. It is further assumed, that the whole of the plates are in the line of the forces, and that the workmanship and riveting are good.

On the excess of strength that should be given to girder bridges, there is a difference of opinion. The Author, however, entertains a conviction that no girder bridge should be considered safe, unless it be tried under four times the greatest load that can be brought upon it; and in wrought-iron tubular-girder bridges, the breaking weight is computed at 12 tons to the lineal foot, inclusive of the weight of the bridge, or about six times the maximum load.

On this calculation, the Torksey Bridge should have been constructed according to the following tables (page 8), which exhibit the strengths, proportions, and other properties of the girders, which are recommended in structures of this kind, and for spans from 30 feet up to 300 feet.

The first column gives the length of the clear span from pier to pier.

The second, the breaking weight of the bridge in the middle.

The third, the area of the plates and angle-iron of the bottom of the girder.

The fourth, the area of the cellular top; and

The last column, the depth of the girder in the middle.

\* It is considered by some engineers, as very important to the strength of these bridges, that the girders should be continuous, or extending over two, or more, spans. This is, no doubt, correct to a certain extent, and although the fact is admitted, yet this consideration is nevertheless purposely neglected, in these calculations; any auxiliary support of that kind acting merely as a counterpoise. It is considered safer, to treat the subject on the principle of compassing each of the spans with simple and perfectly independent girders.

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## R GIRDER BRIDGES.

portions of TUBULAR GIRDER BRIDGES,  
where the depth of the girder is  $\frac{1}{15}$ th of the

Sectional Area of bottom of one Girder.	Sectional Area of top of one Girder.	Depth at the Middle.
Inches.	Inches.	Feet. In.
14.63	17.06	2 4
17.06	19.91	2 8
19.60	22.75	3 1
21.94	25.59	3 6
24.38	28.44	3 10
26.81	31.28	4 3
29.25	34.13	4 7
31.69	36.97	5 0
34.13	39.81	5 5
36.56	42.67	5 9
39.00	45.50	6 2
41.44	48.34	6 7
43.88	51.19	6 11
46.31	54.03	7 4
48.75	56.88	7 8
53.68	62.56	8 6
58.50	68.25	9 3
63.38	73.94	10 0
68.25	79.63	10 9
73.13	85.31	11 6

portions of TUBULAR GIRDER BRIDGES,  
where the depth of the girder is  $\frac{1}{15}$ th of the

Sectional Area of bottom of one Girder.	Sectional Area of top of one Girder.	Depth at the Middle.
Inches.	Inches.	Feet. In.
90.00	105.00	10 8
95.63	111.56	11 4
101.25	118.13	12 0
106.88	124.69	12 8
112.50	131.25	13 4
118.13	137.81	14 0
123.75	144.38	14 8
129.38	150.94	15 4
135.00	157.50	16 0
140.63	164.06	16 8
146.25	170.63	17 4
151.88	177.19	18 0
157.50	183.75	18 8
163.13	190.31	19 4
168.75	196.88	20 0

When the depth of the girders at  $\frac{1}{15}$ th of the span does not exceed 150 feet it has been found that the depth of the span. For spans above 150 feet account of the great weight of the girders is taken of one-fifteenth, in order to keep the deflection as possible, and to prevent oscillation under load. It is objectionable to increase the depth of the span. It is essential to increase the sectional areas of the girders and the ratio of the depths.

GIRDES,  
of the span.\*

Depth at the  
Middle.

Feet.	In.
2	4
2	8
3	1
3	6
3	10
4	3
4	7
5	0
5	5
5	9
6	2
6	7
6	11
7	4
7	8
8	6
9	3
10	0
10	9
11	6

BRIDGES,  
of the span.

Depth at the  
Middle.

Feet.	In.
10	8
1	4
2	0
2	8
3	4
3	0
4	8
4	4
5	0
5	8
6	4
6	0
7	8
7	4
8	0

of the span ;  
found more  
150 feet it is,  
the girder, to  
the centre  
tion under a  
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In these tables, the breaking weights of all the girders are calculated from the formula  $W = \frac{adc}{l}$ ; as for example:—Taking from the table a bridge similar to that at Torksey, 130 feet span;  $W$  = the breaking weight,  $a$  = area of the bottom 63·38 inches,  $d$  = 120 inches, the depth of the girder,  $c$  = 80 the constant deduced from the experiments, and  $l$  = the length, 1560 inches, between the supports.

$$\text{Hence } W = \frac{63 \cdot 38 \times 120 \times 80}{1560} = 390 \times 2 = 780 \text{ tons, the break-}$$

ing weight of the bridge in the middle, or 1560 tons equally distributed over the surface of the platform of the bridge.

From this it will be observed, that after deducting the permanent load of the Torksey bridge (177 tons), there remain 1383 tons, as resisting force to the travelling load of 195 tons, which, according to calculation, is rather more than seven times the greatest weight that can be passed over the bridge,\* 12 tons per lineal foot being assumed as the measure of the strength of a tubular girder-bridge, for a double line of rails, and which will cover all contingencies, either as regards the weight of the bridge, the permanent load, or the forces by which it may be assailed.

Another subject of importance is the force of impact and the effects of vibration, on bridges of this description; and although it is only recently, that the Author has had the advantage of reference to the highly valuable Report of the Commissioners appointed to Inquire into the Application of Iron to Railway Structures, he is nevertheless of opinion, that the principles upon which he has endeavoured to establish the construction of these particular bridges, ever since their first introduction, is perfectly secure, and may be relied upon as being calculated to meet all the requirements and the conditions of railway traffic.

He cannot agree with the Commissioners in some parts of that

\* Since the Table referred to above was completed, and which has been closely adhered to in the calculations of the strengths and proportions of wrought-iron tubular girders during the last 18 months, 1 ton per lineal foot has been taken as the permanent weight of bridges, from 40 feet up to 100 feet span, and the rolling load as 2 tons per lineal foot; and in spans varying from 100 up to 300 feet, the permanent weight of the bridge is estimated at  $1\frac{1}{2}$  tons per lineal foot, and the rolling load also at  $1\frac{1}{2}$  tons per lineal foot. For practical purposes these proportions are found to be perfectly safe; although in spans above 300 feet, where the permanent weight of the structure becomes a large proportional of the load, it becomes necessary to introduce into the calculation new elements as regards strength, as may be seen in those for the Britannia and Conway Tubular Bridges.

#### LAB GIRDER BRIDGES.

experiments therein referred to, do  
t of increased deflection at high veloc  
nducted experiments on tubular gi  
; from 60 feet to 100 feet, the defle  
as possible, the same at all velocities ;  
; at Portsmouth (at some of which  
ighly valuable, and exceedingly interes  
ion, that there must be a considerable  
a weight, rolling over a cast-iron ba  
bridge 60 feet long. It is true the C  
t, have qualified the results obtained f  
ers made upon existing cast-iron rail  
deflection was reduced from an increas  
mounting to  $\frac{1}{10}$ ths of an inch, as produ  
velocity of 30 miles an hour, to  $\frac{1}{4}$ th o  
et span, at a velocity of 50 miles an ho  
t the larger the bridge, and the greater  
girders, the greater will be the reduction  
oad. In the tubular girder-bridges, c  
must be observed, that the Commission  
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ties of girders, composed of wrought-  
ction due to the passing load, appears to  
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It, the Author perfectly concurs in opin  
, that the deflections produced by  
t iron, is nearly as the velocity of impa  
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tions are extremely valuable.

bridges is a part of the inquiry which  
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Commissioners appointed to Inquire into the App  
uctures. Folio. Plates. London, 1849.

to those given in the table, than those of cast iron. The deflection produced in these constructions, by the greatest load, will not be more than one-sixth of the ultimate flexure of the girder. On this subject, the effects of impact and the resistance of tubular girders to a rolling load, were strikingly exhibited, in the experimental tests made on the first construction of this kind, erected for carrying the Blackburn and Bolton Railway across the Liverpool and Leeds Canal, at Blackburn.

That bridge is 60 feet clear span, and three locomotives, each weighing 20 tons, coupled together, so as to occupy the entire span, were made to pass over, at velocities varying from 5 miles to 20 miles an hour, producing a deflection, in the centre of the bridge, of only  $\frac{1}{8}$ ths of an inch. Two long wedges, 1 inch in thickness, were then placed upon the rails in the centre of the span, and the fall of the engines from this, when at a speed of 8 miles to 10 miles an hour, caused a deflection of only  $\cdot 420$  inch, which was increased to  $\cdot 54$ , or about  $\frac{1}{2}$  an inch, when wedges  $1\frac{1}{2}$  inch in thickness were substituted. These were severe tests, and such as would not be generally recommended, as the enormous strength of these girders is now well understood, and they may safely be considered fit for service, after being subjected to the heaviest rolling load, or one-sixth of the breaking weight, taken at high velocities.

The paper is illustrated by a model and by diagrams, showing the construction and dimensions of the bridge, from which Plate 11 has been compiled.

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Previous to commencing the discussion on the paper,—

Mr. C. MANBY, *Secretary*, stated, that the subject of the Torksey Bridge had already been twice brought before the Institution; first, at the meeting of January 29, 1850, when Mr. J. SCOTT RUSSELL begged to detain the meeting for a few minutes, for the consideration of a question of considerable importance to the profession.

The Royal Charter stated the Institution to have been incorporated, “for the general advancement of mechanical science, and “more especially for promoting the acquisition of that species of “knowledge which constitutes the profession of a civil engineer.” It was generally considered, that any question vitally affecting the interests, or professional dignity of Civil Engineers, could not be submitted to a better tribunal than that of the Council of the Institution; to that body, therefore, he would, in the name of a large number of professional brethren, address himself.

It was well known, that for some time past there had been many attempts to restrict the free exercise of the talent and ingenuity of

### BULAR GIRDER BRIDGES.

erfere with the progress of mechanical science by the establishment of Government Boards, in fact, endeavouring to introduce the system of the Ingénieurs des Ponts et Chaussées, which is detrimental to all individual enterprise. In 1847, a Royal Commission was appointed to inquire into the application of iron, in structures exposed to vibration; the Report of that Commission was made public;\* it expressly stated, that "the importance of leaving the genius of science to the development of a subject, as yet so extensive as the construction of railways, was not to be interfered with by legislative enactments with respect to the forms of the iron structures employed the most expedient." Relative to the forms of construction of wrought iron it was also stated, "that it was to be assessed and to promise many advantages, but that no experience has as yet shown the iron powers to resist the various actions of temperature, &c."—"For the reasons above stated, we do not express any opinion upon them." After the issuing of this Report, a gentleman, who had brought iron, from the designs and under the supervision of an engineer of admitted skill and extensive experience, was found by one of the Inspecting Officers of the Ordnance to be unfit for the public service, because it did not conform to the standard, which, in the Report of the Commission was stated to be applicable to cast iron only. The result of this decision, or rather of this application of the standard to a modern invention, was, that the public service was for one month deprived of the use of an important and valuable material. The probable consequence was the condemnation of the railway girder-bridges, which had for years been supporting the greatest loads that could be imposed on the strength of their traffic, and the possible result was the destruction of that magnificent monument of engineering, the Great Western Railway Bridge.

It was necessary to decide, how long the communications would be interrupted, and the invested capital remained at risk. It was for civil engineers to consider whether

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Commissioners appointed to Inquire into the Application of Iron to Structures. Folio. Plates. London, 1849.

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#### TUBULAR GIRDER BRIDGES.

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their reputation should lie under the ban of professional incompetency, because an officer acting under Parliamentary authority interfered, by applying an antiquated rule to a new system of construction, for which it had never been intended. It would be easy to show, that if the bridge, to which he alluded, was not strong enough, half the girder bridges, already constructed, were dangerous for the public service, and yet they had for years performed their duty, and exhibited no greater signs of weakness at present, than they did when they were declared by the same Government officer to be perfectly safe, according to Act of Parliament. He must submit, that it was degrading to the profession, that their reputation should be at the mercy of the arbitrary application of legislative enactments, to structures for which the rules were never intended.

In Mr. Scott Russell's own case; he had constructed some wrought iron girder-bridges, of acknowledged correct proportions, and had guaranteed the result; now by the application of this objectionable rule to these girders, they would probably be rejected, and this had been decided on without any notice to the public, to the Railway Boards, or to the engineers, in any way.

Under such circumstances, he would submit, that the body of the profession naturally looked up to the Council for support and aid, in representing, in the proper quarter, the grievous wrong under which they were suffering, and from the high character and standing of the Members of the Council, he was induced to hope confidently, that the appeal would not be made in vain, for their careful consideration of all the circumstances, and their taking such steps as the Charter would permit, and as would appear to be most prudent, and dignified, for relieving the profession from the trammels which were now attempted to be imposed upon its members.

The subject was again formally alluded to at the meeting of February 5th, 1850, when Mr. J. SCOTT RUSSELL inquired whether any steps had been taken by the Council, in consequence of the statement submitted at the meeting of Tuesday, January 29? He begged to urge the consideration of the manner in which the interests of the public and of the profession, were likely to be affected, by the attitude recently assumed by the Railway Commissioners, in reference to the strength of the wrought-iron girder bridges constructed for railways. It was generally understood, that the excellent Report of the Commissioners for inquiring into the strength of iron structures employed on railways, was intended solely to apply to cast iron and not to wrought iron, and therefore it was essential the question should be set at rest, without further loss of time.

#### LAR GIRDER BRIDGES.

ad to hear of the probability of *the in*  
ive interference being discussed : *h*  
effects of it in a manner which, *he*  
obnoxious. A large timber bridge,  
is, at Lancaster, on a curve in *plan*  
considerable angle, had been objected  
ers, in a letter addressed to the Direct  
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om suggested, that as many engineers r  
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case.

., stated, that the Council had not, as y  
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erference with engineering construction  
LL expressed himself satisfied with t  
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e Members, he begged to withdraw t

a of the previous proceedings,—  
ttention to a model of the *Torksey Bridge*  
transverse section (Plate 11) of the bridg  
gram\* (Fig. 3, page 25), exhibiting th  
periments for the purpose of showing th  
girders, when they were, as in this case  
ier; or, in other words, when each con  
red as covering two openings, formed b

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*Vide* Note, page 28.

He was much indebted to Mr. Fairbairn for pronouncing the bridge to be of sufficient strength ; but the investigation would have been more satisfactory, if the structure had been viewed as composed of continuous girders, each stretching the full length of the platform, and resting upon the three points ; this would be found to add one-fourth to the absolute strength of the part of the girder spanning each opening.

The diagram (Fig. 3, page 25) had been prepared for the purpose of showing the effect of the continuity of the girder, the dotted line showing the curve of deflection, due to weighting the two openings equally with the weight of the structure itself alone ; the full line showing the deflection, due to an additional load of two trains of locomotives upon one span. The latter experiment proved, that the distance from the point of contrary flexure to the centre pier was less than 25 feet, causing a practical reduction of the span from 130 feet to about 105 feet, and adding at least one-fourth to the strength of the bridge. Now any principle that added one-fourth to the strength of a bridge was, he considered, too important to be so lightly passed over ; added to which, he thought the saving of cost in the construction of the work was an important additional consideration.

He thought there was an error in the computation of the proportion between the bottom and the top of the girder, as it would appear, that the area of the rivet-holes had not been deducted from the former, which should evidently have been done. Now the gross sectional area of the bottom being 54.93, and the rivet-holes diminishing the area full 5.25, an area of 49.68 would be left, making the proportion of 51 to 49.68, which corresponded very nearly with the proportion of 12 to 11 given in the paper.

In building the first of these girder bridges (the subject being new to him), Mr. Fowler had been guided by Mr. Fairbairn's proportions, as he was the constructor of the girders ; and it did appear extraordinary, that the dimensions of a bridge of 95 feet span, which had now been open for traffic for full two years, differed materially from the dimensions given in the paper. Now as that bridge had performed its duty efficiently for two years, it would be interesting to learn why Mr. Fairbairn had changed his views as to the requisite dimensions, and why that proportion of the depth to the span, which at so recent a period had been considered sufficient, should now be deemed insufficient.

The drawing represented the strength of one girder calculated according to Mr. Fairbairn's proportion and formula ; therefore the total strength of the two would be equal to 1560 tons. The bridge

#### TUBULAR GIRDER BRIDGES.

l by placing six locomotive engines, weighing the  
ne opening, occupying the whole extent of it,  
a greater test than if a similar weight had been  
ne on the other opening, as, in the latter ca  
ive balanced the other. The effect of placi  
in that situation was to cause a deflection of 1.  
oval of the load, the platform of the bridge ir  
to its original level. Great care was taken to  
n beams had any tendency to approach each  
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f form.

said, the Torksey Bridge had excited the att  
n, from the fact of the Commissioners of Ra  
to the opening of the bridge for traffic, on th  
safety of the public. Mr. Fowler had req  
engineers, to examine the structure, in or  
is to whether the strength of the bridge was  
it, to point out where it required strength  
pection and consideration, the general opinio  
the bridge was sufficiently strong for all pra  
c safety. So far as he could gather from  
appeared to be Mr. Fairbairn's opinion, alth  
from the value and weight of that opinion  
proportions to a bridge of those dimensions.  
ciples which had guided Mr. Fairbairn in  
so entirely different from those Mr. Bidder  
ining the strength of girder bridges, he tho  
state what he believed to be the correct  
should have done some service in laying  
nstitution; and, if wrong, he should have  
corrected.

which Mr. Fairbairn had directed atten  
s of the top and bottom of the girders, and  
proportions between them should be in the  
it any excess of those proportions was so m  
employed; that is to say, if the 12 was  
so much weight added, without imparting  
h. Mr. Bidder thought that must be e  
e tabular statement, instead of those prop  
g rigidly adhered to, the ratio of 12 to  
ed. He also believed Mr. Fairbairn was  
he increase in dimensions over any assu  
to the weight of the bridge, without be

any addition to its strength. The top of the bridge was exposed to compression, and the bottom to tension: between those two there existed the neutral axis; therefore, the compressing force on the one, and the tensile strength on the other, must be equal; the result must then be, that any addition to the bottom only removed the neutral axis so much further from the top, bringing it so much nearer to the bottom: it was true that it might not gain all the advantage of that addition of metal to the bottom, but it was certain that some additional strength was obtained. Supposing the top and bottom to be in the proportion of 11 to 12, the paper implied, that if 11 was added to the bottom, making it 22, no strength would be added to the bridge, but that it would be encumbered by an extra weight of metal. Mr. Bidder denied that position, and thought that, the neutral axis being removed from the top, by any addition of metal to the bottom, even if that addition amounted to 34, the strength of the bridge would be increased by one-third; adding 50 per cent. in weight, and gaining 30 per cent. in strength. He did not mean to say that would be a judicious distribution of the metal, but he thought it wrong to suppose it would perform no duty, and much less that it would be injurious. He thought it incorrect to fix any arbitrary limits to two quantities increasing in different ratios, and in that respect he was decidedly at issue with the deductions of the paper.

He also dissented from the notion, that the depth of a girder should be restricted within any given limits; in practice, engineers were scarcely ever able to fix such limits, being generally guided by local considerations. The question of the proper depth of a girder, was at present entirely unascertained, and it was clear the Author of the paper could not have arrived at any precise notion on the subject, because the original table sent with the paper assigned the proportion of  $\frac{1}{15}$ th of the span for the depth of a girder of any span, but in the amended table, subsequently transmitted, that proportion was only retained up to spans of 150 feet, and the proportion of  $\frac{1}{15}$ th was adopted for all greater spans.

Theoretically, the top and bottom could not be placed too far apart; in practice, the consideration was, the least amount of metal that would enable the top and bottom to be placed at a proper distance to prevent the sides from buckling. That was a question which could not be decided mathematically, but must be determined entirely by experiment. He was not aware what reasons had induced this alteration of the table, within the last fortnight; but he thought it would not be wise to adopt blindly any empirical limit. He thought it a mistake, to endeavour to ascertain the

strength of a girder by finding the greatest weight it would sustain, and he was not aware of any received coefficient, so large as 20 tons to the square inch; the largest he knew of was 16 tons.

He agreed in the observations on the small effect of vibration, by railway trains, passing over bridges; he believed it to be a mere ghost, raised by mathematicians to frighten engineers as to the strength of their structures, and he thought the engineers were bound, as standing between the mathematicians and the public, to apply to their deductions the principles of common sense. When once a certain length of girder was exceeded, the effect of concussion ought to be left entirely out of consideration. Mr. Fowler had placed on his bridge an extraordinary weight of 222 tons on one opening, and it was asked, what would be the effect of that weight in motion, treating it as 222 tons on one pair of wheels, propelled in a given direction; it must be remembered, that weight would be distributed over 72 wheels, each having a spring, and as that weight could only operate on a girder through the instrumentality of the rails, which were nearly 6 inches in depth by 1 inch in thickness, it would be seen that the effect, whether vertically, or laterally, would be absolutely nothing on a structure of that weight and rigidity. The fracture of a rail, or a chair, laterally, by the action of a train; was a thing of rare occurrence, except when the carriages got off the line; as an engineer, he considered, practically, that might be omitted from consideration. It must then be supposed, that the strain would act vertically and snap the girder; but there was not a rail which was not subjected, by every train passing over it, to a much greater strain than any on the bridge in question. In his opinion, the effect of concussion on any bridge of such a span, with girders of such dimensions, was a matter unworthy of notice.

In making a few observations, for the purpose of showing that the bridge, as constructed by Mr. Fowler, and so retained, in opposition to the report of the Inspecting Officer, was abundantly strong, he desired it might not be supposed that he wished to reflect on that gentleman, who had never shown the slightest desire to throw impediments in the way of any engineer, or that he should be supposed to wish to do more, than to have the question fairly and honestly discussed before the Institution. Captain Simmons had stated in his report, that he should be satisfied, if one opening of the bridge would sustain a load of 400 tons, with a strain of 5 tons to the inch, the dead weight of the bridge being 175 tons, leaving 225 tons for the rolling load. In order to submit it to a severe test, Mr. Fowler had placed 222 tons on one opening, but he would ask, under what circumstances of ordinary traffic was the bridge liable to be exposed to

that test? It could only be on the supposition of three coupled engines travelling on each line, without any carriage being attached to them, and meeting on one particular opening. In practice, three coupled engines were not often attached to a heavy goods train, and it was not probable that three engines would often go out alone. The supposed test, however, required the same weight on both lines; it might be fairly presumed, that one of the sets of engines would have a train attached to it, and resting on the other opening; so that the effect would be diminished on the portion on which the engines rested. After subjecting the bridge to that weight of 222 tons, the deflection was ascertained to be  $1\frac{1}{2}$  inch. Captain Simmons said, if it would bear that weight and not have more strain than 5 tons on the inch, he would be satisfied; whatever extent of weight that was derived from, the effect on the tension of the iron would be the same, and taking the strain on the bottom to be 5 tons to the inch, the deflection ought to be 2 inches; it was actually only  $1\frac{1}{2}$  inch, therefore the experiment proved the strain was not 5 tons to the inch. Mr. Bidder had not been quite satisfied on that point, until Mr. Wild's experiments, on a similarly proportioned beam, showed the point of bearing was practically reduced from 130 feet to 105 feet, by the continuity of the tubes, over the centre pier, by which the length of the girder, exposed to strain, was not only reduced, but the weight being equally diffused, was also diminished, and therefore the deflection would be reduced as the square; this induced the conclusion in his mind, that the Torksey bridge was abundantly strong for all purposes of public safety.

Mr. EATON HODGKINSON said, it was with great reluctance that he made any observation in the absence of Mr. Fairbairn, differing as he did from him in many of his conclusions. Mr. Fairbairn had in his paper adduced a formula, with a coefficient attached, for the strength of wrought-iron tubes; but the adequacy of that formula might be questioned; indeed if the tubes were made as proposed in the paper, it was doubtful whether it might not be unsafe and dangerous, to rely upon the formula.

When Mr. Hodgkinson made experiments, many years ago, to ascertain the strength and best form of cast-iron beams, he used the same simple formula, with a coefficient deduced from numerous practical experiments on the fracture of cast-iron beams. This formula depended merely on the tensile strength of the bottom rib, and on the depth and length of the beam. These data he considered sufficient, for that material; for in cast-iron beams, of the best form, there would be more than twice as much metal

## ORDER BRIDGES.

all the rest of the beam

the new tubular girders. It rendered it difficult to draw such material of more perfect

table for cast-iron beams, with tubes of wrought iron, was alone included) bore but a small area; and the sides of the beam, as all the rest.

without the angle-irons the sectional area, to the plate a formula that would reject the estimation of its forces by arithmetical computation or knowledge of the present day.

that the formula was applicable; but the tubes in Mr. Fairbairn's applicability to tubes of the same length; and especially to tubes of a bridge, the strength of which

the strength of tubes in general

the bottom of the tube differed in form, it would be necessary to find the neutral line, and this would be difficult. Secondly, it would be necessary to find the forces exerted by each of the plates of the tube; or, in other words, the moments must be equated, to find the leverage from the length of

the tube of the second form, the formula

$$\frac{d^3 - b'd'^3}{3ld}$$

the external and internal depths and internal breadths,  $l$  the distance

obtained from these experiments, the bottom ribs, in the middle, was as much as in its section, as all the

between the supports,  $f$  the strain per square inch of section, sustained at the top and bottom of the tube, and  $W$  the weight, which being laid on the middle of the tube, would produce that strain.\*

If  $f$  be taken at eight tons per square inch, it would be within the elastic force of the material: some tubes of simple plates had borne as much as double that pressure, or more.

Mr. Fairbairn asserted, that the comparative thickness of the top and the bottom of a tube, should be as 12 to 11, this having been the case in the large tube made in London; but Mr. Hodgkinson contended, that there could be no constant proportion between the thickness of the top and of the bottom. A tube of one thickness of metal might be well proportioned, but double the thickness would render it very much out of proportion. The resistance of thin plates to a crushing force, applied in the direction of their length, was found to vary nearly as the cube of the thickness. Doubling

\* For the manner of computing the strength of the Conway Tube, see Appendix, by Mr. Hodgkinson, in the Report of the Commissioners on the Strength of Iron, pp. 174, 175.

In tubes formed of simple plates, with cells at the top, as in those made by Mr. Fairbairn, the section of the top and bottom being nearly equal, the strength might be computed, by assuming another form, of nearly equal strength, and easily calculable, in the following manner:—

Fig. 1.

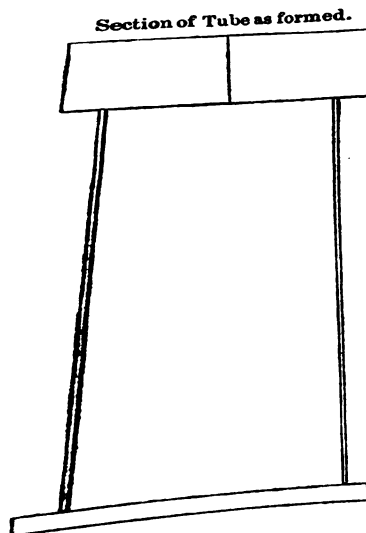
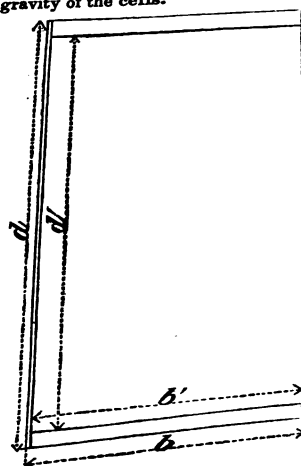


Fig. 2.

Section of Tube nearly equivalent in strength, the thickness of the bottom and sides being equal to those in the former; and the top of equal area of section to that of the cells in the former, and placed at the height of the centre of gravity of the cells.



# DER BRIDGES.

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were made of half the thickness, or  $\frac{3}{4}$ ths inch thick, was not corrugated, or wrinkled in the top, though it was considerably shortened, by the compression there, and had taken a deflexion of 7.33 inches, with a load of nearly 103 tons, in the centre, and a pressure in the top plates of 18 tons per square inch of section. Tubes of half that thickness at the top would probably have wrinkled with a few tons per square inch of section there.

These facts showed the great importance of increasing the thickness of the plates of tubes; and his experiments rendered it evident, that square cellular tops might be advantageously dispensed with, by increasing the thickness of the plates on the top, by riveting them together, and thus placing the resisting forces at the top and bottom of the tube as far asunder as possible. If, also, in addition, longitudinal ribs of cast iron were riveted to the plates along the top, to resist compression, when the wrought iron failed, a great increase of strength would thus be obtained, as had been shown by his experiments.

Mr. C. H. WILD begged first to read the following extract from the second report by Capt. Simmons, the Government Inspector:—

“In reply to the question, ‘Whether if I still remain of opinion that this viaduct cannot be opened with safety to the public, what further strengthening will be necessary?’ I have to state that for reasons before adduced, I do not consider, that the viaduct can be opened for the continuous passage of trains, with safety to the public, and that it will not be in a condition to be opened, until it shall have been so strengthened, that a load of about 400 tons, (including the weight of the beams themselves, and all the standing parts of the bridge), distributed equally over the platform of one span, shall not produce a greater pressure upon the top plate of the girders, than five tons per square inch.”

In consequence of this opinion, Mr. Wild had, at the request of Mr. Fowler, entered into calculations, to ascertain what the compressive strain on the top of the bridge would be, under the prescribed conditions, when it was found, that it would be less than 5 tons per square inch, the limit defined in the report. As this result differed from that arrived at by the Government Inspector, recourse was had to experiments to confirm the truth of the calculations.

Among the many points noticed in Mr. Fairbairn’s paper, was one which he must consider not only unphilosophical, but positively dangerous. The paper said, “It is considered by some engineers, as very important to the strength of these bridges, that the girders should be continuous, or extending over two, or more spans. This is, no doubt, correct to a certain extent, and although the fact is

admitted, yet this consideration is purposely neglected, in these calculations; any auxiliary support of that kind acting merely as counterpoise. It is considered safer to treat the subject on the principle of compassing each of the spans with simple and perfectly independent girders."\*

The importance of the effect of continuity was acknowledged by all authorities, so that it could not be admitted, that this was an element, the consideration of which might, with any propriety, be neglected. The Torksey bridge consisted of two openings, each 60.30 feet; the two being spanned by a continuous girder resting on the central support. If such a beam was placed on the three supports A, B, C (Fig. 3), and were loaded uniformly, it would assume the shape of the dotted line  $A m B n C$ . It was evident that between A and  $m$ , the upper portion of the beam would be compressed, whilst on the part  $m n$ , over the support, the reverse effect would be produced; the beam might therefore be divided into three parts. At the point of contrary flexure,  $m$ , all horizontal forces ceased, and there existed merely the vertical strain, due to the suspension, at that point of half the weight of the beam  $A m$ . If the continuous beam were hinged at the points of contrary flexure, and so divided into three independent beams, the previously existing conditions would remain unaltered. This being the case, it would be an evident error, if in calculating the strength of such a beam,  $A B$  only were taken as its length. In order to check, practically, the calculated position of the point of contrary flexure, the experiment was tried on a large wooden model, by loading it, first with such weights as represented the constant load due to the structure. The model beam then took the form shown by the dotted line in Fig. 3, and the point of contrary flexure was found to be  $30\frac{1}{2}$  inches from the point B. The model was then severed and hinged at that point, when the curve and the deflection were found, as might have been expected, the same as before. In order to ascertain the point of contrary flexure in a beam loaded as prescribed by the Government Inspector, over one span only, an additional weight was added, having to the weight previously applied on that span, the same proportion as 400 tons to the prescribed load, had to 150 tons, the weight of the structure. The point of contrary flexure then approached to within  $21\frac{1}{2}$  inches of the central support. The beam was again severed and hinged at that point, and the curve was formed as regularly as before, the deflection on the heavily-loaded side being  $5\frac{1}{2}$  inches. The beam was then cut in half, making it into two detached beams, the end

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\* *Vide ante*, page 6.

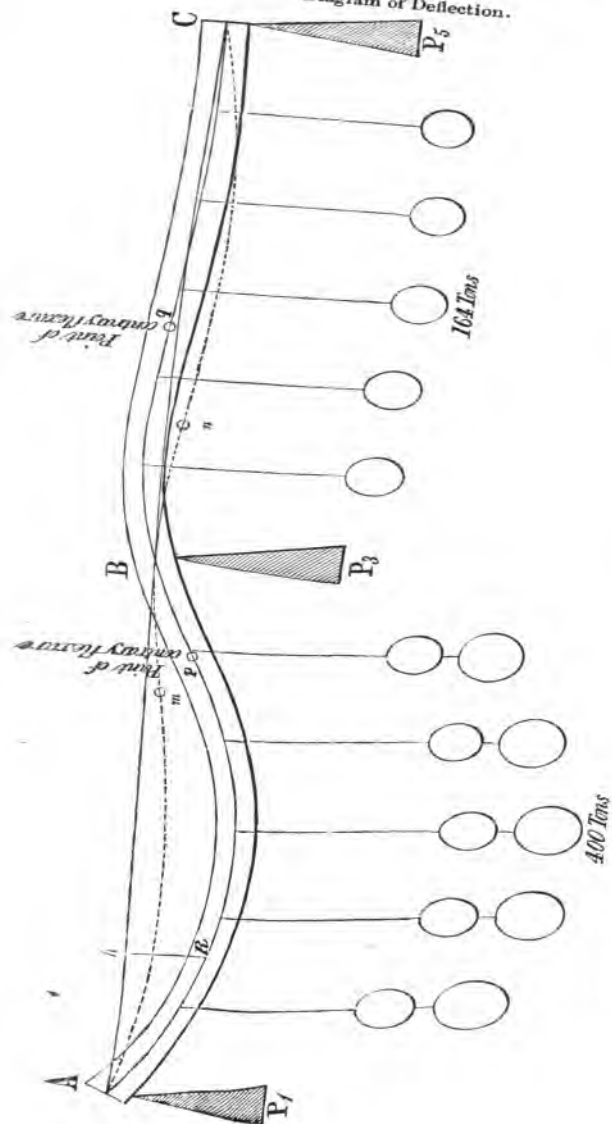
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# TUBULAR GIRDER BRIDGES.

Fig. 3.  
Diagram of Deflection.

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The dotted line represents the position of the girder as deflected by its own weight only, viz., 164 tons distributed over each span.

#### ER BRIDGES.

n it was found on the heavy increased to  $9\frac{1}{2}$  inches. As much of the deflection to the same amount, been produced by the weight proportion borne by the weight on in the detached beam, was the same deflection in the continuous and the position of the point of load in the proportions prescribed was easy to calculate the strain on the bridge. The virtual length  $1\frac{1}{2} = 108\frac{1}{2}$  feet: the load upon  $100 = 333$  tons, or upon each side 83 tons. If, for the sake of comparison, the strain upon

4.67 tons per inch;

of 5 tons per inch, defined

corroborated the truth of the fact that the compressive strain upon the girder, to be less than that of the beam. The Inspector had condemned the bridge, but it had remained for some considerable time. In consequence of the sacrifice, the Railway was deprived of the use of their preferred line, not in consequence of the failure to provide adequate strength, but in consequence of the pernicious effects of Government. The necessary consequence of the war was that when officers whose duties were connected with the control of civil works were engaged by Mr. Fowler to examine the bridge and deflexion of the Torks, the result of the meeting the result appeared clearer than by mere

statement, read as follows:—

as that now under discussion of calculation more extended. In order to form

correct judgment on the question, it is necessary not merely to obtain a general approximate notion of the strength of the bridge, but to ascertain, with all possible exactness, the nature and amount of the strains to which the structure is exposed; and this can only be done by a comprehensive process of calculation, which, though more laborious, will be more satisfactory.

"As no doubt appears to be raised as to the sufficiency of the transverse bearers supporting the platform, the only question is, as to the strength of the main wrought-iron tubular girders extending across the stream, and to this alone, therefore, attention need be directed.

"The problem for determining the strength of a beam, resolves itself, in this case, as in many others, into the following question—'When a certain beam is loaded with a given weight, what is the greatest longitudinal strain, either of extension, or compression, on any of its fibres?' It is well known, that when an elastic beam, supported at both ends, is weighted in the centre, the upper fibres of the beam are compressed and the lower fibres extended. Now, it has been well ascertained what degree of longitudinal strain may be applied to these fibres with safety; and therefore, if the ratio can be established, which exists between the weight a girder is supporting, and the compressive or tensile forces on its top and bottom plates, we have effectively determined the question, whether such girder is, or is not, sufficiently strong. For example, Mr. Hodgkinson states, in his calculations on the Britannia and Conway tubular bridges, (Report to the Iron Commission, pp. 171 and 178), that the metal of the tubes may be allowed to bear, at a maximum, 8 tons per square inch compressive strain, and about 10 tons tensile strain; the ultimate strength in each case being about half as much more. Now, if we can show, that in the Torksey bridge girders, when loaded to the utmost, the greatest compressive strain is little more than half 8 tons, and the greatest tensile strain less than half 10 tons, we establish, to all intents and purposes, the sufficient strength of the bridge.

"The general rules for determining the strains on beams of a perfectly elastic material (as wrought iron may be assumed to be), are well established, and very generally known; but in attempting to apply them to the Torksey bridge, we are met at the outset by a peculiarity in the case, which throws some difficulty in the way.

"Each girder, instead of extending over one span only, is of double length, being continued over the two openings, and being supported at three points A, B, and C, as shown in Fig. 3, page 25. Now, it must be apparent, almost at first sight, that this continuity will increase the strength of the girder, as far as one opening is

supported at both ends, and thus we have the common problem of a simple girder supported at both ends, and loaded with a weight distributed over its whole length; this beam being, however (for this is the important point), considerably shorter than the span of one opening of the bridge.

"Now, this difference of length, or, in other words, the distance of the point of contrary flexure from the centre pier, is determined by the mathematical investigation already alluded to;—for the loads above given, it comes out something less than 23 feet, leaving 107 feet for the effective length of the beam. The value of the advantage gained by the continuity of the girder is thus apparent; for, instead of a girder 130 feet long, bearing 400 tons, we have, effectively, a girder only 107 feet long, bearing 330 tons; giving an increase of strength of rather more than one-third.

"The remainder of the calculation, necessary to determine the greatest longitudinal strain on the fibres of this beam, is very simple, and follows the ordinary rules.

"The beam is supposed to be perfectly elastic, and the neutral line is found according to the well-known proposition, that in such a beam it will pass through the centre of gravity of the section. This brings it 56 inches from the bottom, or 64 inches from the top, of the girder.

"The moments of the strains on each part of the section (omitting the rivets and angle-irons at the bottom), are then taken round the neutral line, and by equating these, in the ordinary manner, with the moments of the load on the beam, we obtain:—

$$\begin{array}{l} \text{The greatest compressive strain on} \\ \text{the top-plates of the girder, with} \\ \text{a load of 400 tons} \end{array} \left. \begin{array}{l} \\ \\ \end{array} \right\} = 4.55 \text{ tons per sq. in.}$$

$$\begin{array}{l} \text{The greatest tensile strain on the} \\ \text{bottom-plates} \end{array} \left. \begin{array}{l} \\ \end{array} \right\} = 4.00 \text{ " " "}$$

"It is remarkable, how closely the results obtained by Mr. Wild's experiments agree with the results of the mathematical investigation, the general form of the deflexion curve being nearly identical in both cases, although the two classes of results were obtained entirely independent of, and uninfluenced by each other.

"The experimental distance of the point of contrary flexure, where the model beam was cut across, from the centre pier, is a little less than 22 feet; as calculated, it is 22 feet 11 inches. For the unloaded beam, the calculation gives the distance of this point = 32 feet 6 inches; the experiment = 30 feet 6 inches. The experiment gives the greatest compressive strain = 4.67 tons; the calculation = 4.55 tons.

The deflection of the bridge is, to what it would be, if the girder extended over one span only, by calculation, as 100 to 170, whilst by experiment it is found to be as 100 to 180.

"The deflection of the bridge due to the rolling load, comes out by calculation  $1\frac{1}{8}$  inch; and when the bridge was loaded with locomotive engines, the actual deflexion was found to be about  $1\frac{1}{2}$  inch.

"The most important result, however, is that already given in reference to the strain, as this applies directly to the question of the strength of the bridge. If the experiments and calculations are to be relied upon, they prove, that when the bridge is loaded with the defined test weight, the utmost compressive strain on the plates of the girders is less than 5 tons per square inch, and the utmost tensile strain only about 4 tons per square inch.

"Let these results, therefore, be compared with the statements of the best authorities, that a compressive strain of 8 tons, and a tensile strain of 10 tons, may be borne without danger, and the question is at once decided, whether or not the Torksey bridge is sufficiently strong."

The following are the calculations alluded to in the foregoing remarks:—

*Investigation of general formulæ applicable to the Torksey Bridge.\**

A beam of uniform section, and of perfectly elastic material, is supported horizontally at three points, A, B, and C (Fig. 3, page 25), the support B being midway between the two others. The two spans, A B, and B C, are each loaded with different weights, distributed uniformly over the length of each span respectively, the weight on the part A B being greatest.

To determine the deflexion curve of the beam, and the strength of the part A B,

Let  $l = A B$ , or  $B C =$  the length of each opening.

$\mu =$  weight per lineal unit distributed over the space A B.

$\mu_2 =$  ditto over the space B C.

$\left. \begin{matrix} P_1 \\ P_2 \\ P_3 \end{matrix} \right\} =$  pressures upon the three supports A, B, C, respectively.

$x = A h =$  horizontal distance from A of any point R in the neutral line of the beam.

$y = h R =$  the deflexion at that point.

\* A more extended investigation on the subject of continuous beams has been given by the Author of these remarks, in Mr. Edwin Clark's work on the Britannia and Conway Tubular Bridges, which may be referred to for further explanation and application of the mathematical processes here employed.

# GIRDER BRIDGES.

neutral line of the beam, whose position R A of the beam is held in equilibrium.

rotation of the beam,  $= \mu x$ .  
 called into operation on the transverse section at R.

Quantity of moments must therefore occur. *i. e.*, the sum of the moments occurring to turn the part R A round must be equal to the moment of the first, which is the reaction.

$P_1$  acts at a perpendicular distance of this force is  $= P_1 x$ .

It is considered as collected at a point, the moment of this force  $= \frac{\mu x^3}{2}$

the moment of the elastic force

$$+ \frac{\mu x^3}{2} = P_1 x.$$

$$= P_1 x - \frac{\mu x^3}{2}.$$

of elasticity of the beam, and the transverse section round the neutral line, will be represented by the equation,

$$- E I \frac{d^2 y}{dx^2}.$$

$$= \frac{\mu x^3}{2} - P_1 x.$$

entering the inclination to the horizontal line at B, by  $\beta$ , so that at that point

$$\frac{\mu}{6} (x^3 - l^3) - \frac{P_1}{2} (x^2 - l^2)$$

$$= \frac{\mu}{6} \left( \frac{x^4}{4} - l^2 x \right) - \frac{P_1}{2} \left( \frac{x^3}{3} - l^2 x \right)$$

section curve from A to B.

At the point B, when  $x = l$ , we know that  $y = 0$ ; therefore, by substituting these values in equation (III.), we obtain,

$$(IV.) \quad \tan \beta = \frac{l^2}{24 EI} (3 \mu l - 8 P_1)$$

Now, by applying a similar process to the part B C of the beam and remembering that the angle  $\beta$  must in this case have a contrary sign, we obtain,

$$(V.) \quad \tan \beta = \frac{l^2}{24 EI} (8 P_2 - 3 \mu_2 l)$$

Comparing this with equation (IV.) we obtain,

$$(VI.) \quad 3 \mu l - 8 P_1 = 8 P_2 - 3 \mu_2 l.$$

By the principle of equality of moments round B, we have

$$(VII.) \quad P_1 l + \frac{\mu_2 l^2}{2} = P_2 l + \frac{\mu l^2}{2},$$

whence by substitution with equation (VI.)

$$(VIII.) \quad P_1 = \frac{7 \mu l - \mu_2 l}{16}, * \text{ and}$$

$$(IX.) \quad P_2 = \frac{7 \mu_2 l - \mu l}{16},$$

and since  $P_1 + P_2 + P_3 = \mu l + \mu_2 l$ ,

$$(X.) \quad P_3 = \frac{5}{8} (\mu_2 l + \mu l)$$

To find the point of contrary flexure in the curve A R B; or where  $\frac{d^2 y}{d x^2} = 0$ .

Referring to equation (II.), we have  $0 = \frac{\mu x^2}{2} - P_1 x$ ,

or  $x = \frac{2 P_1}{\mu}$  at the point of contrary flexure.

It is evident that at this point,  $\phi = 0$ , i. e., there are no elastic forces exerted, and therefore there are no longitudinal strains, either of extension or compression, on any of the fibres of this section of the beam.

We may now proceed to calculate the strength of the part A B of the beam; and this resolves itself into the question, What is the greatest longitudinal strain on the fibres of the beam, when bearing a given load?

Let the load distributed over the length AB =  $\mu l$ , as before.

Now in order to find the place in this length where there is the

\* If  $\mu = \mu_2$ , i. e. if the load is equal on both sides of the centre pier,

$$P_1 = P_2 = \frac{3}{8} \mu l,$$

$$P_3 = \frac{10}{8} \mu l.$$

## TUBULAR GIRDER BRIDGES.

in the fibres, or where  $\phi$ , the moment of the  
maximum, differentiate equation (I.) and make  $\frac{d\phi}{dx} = 0$

$0 = P_1 - \mu x$ , or  $x = \frac{P_1}{\mu}$  at the place of greatest

It is observed from equation (XI.), is half  
of the beam and the point of contrary flexure.  
By comparing between equations (I.), (VIII.), and (XI.)  
the moment of elastic forces at the section of greatest

$$\phi = \frac{(7 \mu l - \mu_1 l^2)}{512 \mu}$$

It is able of proof,\* that if  $f$  = the longitudinal strain  
of area, on any fibre of the beam;  $c$  = distance of  
the neutral line, and  $I$  = the moment of inertia  
of the girder round the neutral line; then

$$\text{Moment of elastic forces} = \phi = \frac{f}{c} I.$$

By equation (XIII.), at the section of greatest strain

$$\frac{f}{c} I = \frac{(7 \mu l - \mu_1 l^2)}{512 \mu}$$

$$\text{or, } f = \frac{c (7 \mu l - \mu_1 l^2)}{512 I \mu}$$

By using the proper value of  $c$ , will give the greatest strain  
of extension or compression, on any of the fibres of the beam  
and thus determine the *strength* of the beam to resist a

### *Application to the Torksey Bridge.*

The following are the values of the given quantities for  
the question:—

$l$  = width of each opening = 1560 inches.

$W$  = load on AB = 400 tons, or for each girder = 200 tons

$w$  = load on BC = 164 tons, or for each girder = 82 tons

$E$  = modulus of elasticity, is taken at 10,000 tons† for a  
one inch square.

### *To find the position of the neutral line.*

It is known that when the material of a beam is perfectly  
elastic, the neutral axis of any transverse section passes through  
the centre of gravity.

\* Vide Britannia and Conway Tubular Bridges. Equation i., page 244

† The value used for the deflexion of the Britannia and Conway Tubular  
Bridges.

By the application of this rule to the section of the Torksey bridge girders, the neutral line is found 64 inches from the top, or 56 inches from the bottom of the section.

*To find the moment of inertia I of the transverse section round its neutral axis.*

Since we have  $I = \sum p^2 \Delta k$ , the moment of inertia is obtained by adding together the moments of all the separate parts of the section.\* The moments of the horizontal plates are found by simply multiplying the area of each by the square of its vertical distance from the neutral line; those of the vertical plates by the application of well-known analogous rules. The following are the results, derived from two independent computations. The dimensions are taken in inches.

*Moment of inertia of the section of the girder, round the neutral line.*

*Compressed portion—*

Top plates . . . . .	73,700
Vertical plates of cells . . . . .	41,700
Bottom plates of cells . . . . .	51,700
Portion of side plates . . . . .	21,100

Total moment of compression . . . . . 188,200

*Extended portion—*

Portion of side plates . . . . .	28,500
Bottom plates . . . . .	155,800
	184,300

Total sum of moments = I . . . . . 372,500

The values of the pressures on the three points of support are obtained from equations (VIII.), (IX.), and (X.) They are for each girder

$$P_1 = 82 \cdot 375 \text{ tons}$$

$$P_2 = 23 \cdot 375 \text{ ,,}$$

$$P_3 = 352 \cdot 500 \text{ ,,}$$

The value of  $\tan \beta$  ( $\beta$  being the angle the girder makes with the horizontal), at the point B, is obtained from equation (IV.)

$$\tan \beta = -0 \cdot 0014955$$

The distance of the point of contrary flexure from A, is, by equation (XI.) = 1285 inches, or 22 feet 11 inches from the centre pier.

The deflexion of the loaded span of the beam is obtained by equation (III.) and that of the unloaded span by one similarly deduced. The deflexion of the unloaded beam may be found in a

\* Vide Britannia and Conway Bridges, page 244.

#### TUBULAR GIRDER BRIDGES.

length was not considered sufficient. General formulae were very useful, but they might be misapplied, and there was a record, of two engineers arriving at a different result from their calculations of the breaking weight of the bridge, as they both used the same rule.

Mr. Eaton was at all convinced, that a rolling weight in motion had a more pernicious influence than a weight remaining stationary. It had been asserted. The most conclusive experiments made by the Iron Commissioners were those on stone bridges, as detailed in their Report; in which the stationary weight produced a deflexion of 1 inch on a span of 48 feet, whilst it was only increased to 1.5 inches when the train passed over the bridge at the rate of 10 miles an hour. The experiments at Portsmouth made by the Iron Commission, though arranged with great care, were considered to be of little value, on account of the bridge being on too small a scale, and owing to the velocity of the train being too near the bottom of a curve, resembling a portion of the centrifugal railway, which he did not consider a satisfactory system. He thought the fairest test of the strength of the Torksey bridge would be, to run over it a heavy train loaded with coal, or iron, and drawn by a steam locomotive, at various velocities, from 5 miles to 30 miles an hour; and also trains of passenger-carriages, proportionably loaded, running at various speeds, up to 60 miles an hour; and to note the deflexions caused by each of these trains, which would be carefully noted. The experiments thus suggested should be made on the bridge itself, with the heaviest goods trains that could ever pass over it, and at the highest velocities they were capable of attaining, could not fail to give a result, if, as he believed, the maximum deflexion obtained was not more than half that caused by the greater weight of a stationary load. At rest, it might be considered a decisive proof of the safety of the construction.

He attached much importance to the effects of impact, and he was much struck by Mr. Eaton Hodgkinson's recent experiments, which proved that the shocks to which railways were liable under certain circumstances, from an accidental obstacle on the rails, might produce a positive injury to this bridge.

The continuity of the girders in the Torksey bridge was of vital importance, and would venture to allude to the fact that the bridge over the Dee, in confirmation of the position.

A single cast-iron girder might give way with

warning, but it was a very different case when the girders were continuous. The Dee bridge was quite as strong, in proportion, as that over the Ouse, at York, or any of the bridges of the same sort that had been built, and which had stood safely for years; the only difference was, that in the Dee bridge the girders were independent of each other, and in the former bridges, of the same sort, they were continuous. He looked on that want of continuity in the girders of the Dee bridge, to which unfortunately, he did not give sufficient attention when he first inspected it, as the sole cause of its failure.

Professor WILLIS hoped he might be allowed to add a few words, on the experiments as to the effect of velocity on the safety of bridges, as he had been engaged in carrying them on. He thought if General Pasley had studied more carefully the Report of the Commissioners, he would have modified his observations, with respect to the possible increase of deflexion from velocity, in a bridge of 130 feet span, comparing it with one of 80 feet. The theory and deductions given in Appendix B., of that Report, had shown, that the increase of deflexion produced by the velocity of the load, diminished rapidly, when the length of the bridge was increased, and that in so great a span as that of the Torksey bridge, this increase was so small as to be wholly insignificant. In framing their Report, the Commissioners had guarded this assertion in every manner, supporting the theory by experiments, tried with the utmost accuracy, permitted by the limited time and means at their disposal. The experiments at Portsmouth were tried on bars of a large size, considered as experiments, but their length of 9 feet was necessarily small, compared with the span of real bridges; and it was true that in them the increase of deflexion by velocity had developed itself to an extent that was of serious importance. He had, however, shown by theory, and by the subsequent experiments at Cambridge, that as the span and weight of the bridge increased, and the statical deflexion diminished, the increase of deflexion from velocity became wholly unimportant. The results of those investigations should convince engineers and the public, that from that cause they had nothing to fear. He was quite ready to defend the principle on which the velocity was obtained, in the experiments at Portsmouth, namely, by allowing the load to run down an inclined plane, and then conducting it by a gentle curve to the horizontal direction, so as to pass it steadily over the horizontal trial bars. He saw no other method of performing the experiments, and could not understand what the centrifugal railway, alluded to by General Pasley, had to do with the question.

Mr. R. Willis. The experiments at Portsmouth showed that effect to be produced by the bars of cast iron, although the bars resisted the effect of blows inflicted by Captain James, in his month, produced "no very perceptible effect." He was prepared to receive the opinion of Mr. R. Stephenson, Mr. Hodgkinson, and Mr. Fairbairn. Still, he felt bound to consider the form of tubular bridges the best that could be theoretically and practically. He thought the material was thus placed in respect, whether he adopted the experiments and investigation as that gentleman had devoted much attention to the compression of iron, in the most advantageous manner. It had been long known and exemplified by Emerson and other writers, that continuous beams were much stronger than isolated beams.

Mr. J. Scott Russell wished to bear testimony to the value of the bow-string form, which was that of the trussed iron, in the most advantageous manner. He thought that he had been to examine carefully, and he thought, that no arrangement of the Commissioners' Report, that by Professor Willis, and the result of which he was, therefore, prepared to place great confidence.

The main point in the present discussion was, whether the strength of the tube across the central pier should be admitted to place great confidence. Mr. Wild, which were the only portion of the bridge was as great as might be necessary to have been more satisfactory than that made by Professor Willis, and he thought, that no arrangement of the Commissioners' Report, that by Professor Willis, and the result of which he was, therefore, prepared to place great confidence.

Mr. Pole, and the experiments of Mr. Wild, which were completely demonstrated the advantages of the continuity of the bridge was as great as might be necessary to have been more satisfactory than that made by Professor Willis, and he thought, that no arrangement of the Commissioners' Report, that by Professor Willis, and the result of which he was, therefore, prepared to place great confidence.

\* Wild Report of the Iron Commission, page 121.

strength of the girders of the Torksey bridge, the decisions with respect to its presumed instability were valueless.

The model exhibited the form of the girder in its actual condition, and demonstrated the enormous addition to its strength at the expense of a very small quantity of material; it was certainly, then, a radical error to omit so important a consideration as the continuity over the central pier, and any formula which neglected that element could not be accepted by the profession; but it was even less excusable, that a structure, which had been shown, both theoretically and practically, to possess the requisite amount of strength, should have been rejected because an officer of the Government, acting under the sanction of an Act of Parliament, had applied to a comparatively new system of construction, an antiquated formula, for which it was never intended.

Mr. FAREY addressed to Mr. Fowler several questions, as to the thickness of the material in the different parts of the girders, the arrangement of the plates of iron, and the value of the angle-irons in conducing to the strength.

The metal in the vertical sides should not certainly be overlooked, whether it must be considered as mere dead weight, tending to break down the girder, or whether it contributed to the actual strength. All that was stated on the subject, in the paper, was, "that the sides were to be sufficiently rigid to retain the girder in shape." It was, however, a question, what thickness of metal would suffice for that purpose, and what system of bracing should be adopted to prevent buckling. According to Mr. Fairbairn's formula, the sides were not to be considered in calculating the strength of the bridge, in which case it would be an improvement to omit them entirely from the bridge; or, on the other hand, should they not be introduced into the formula, as they would certainly introduce themselves in the consideration of the cost of the bridge?

It appeared, that in the dimensions taken for computing the sectional area of the metal, no allowance was made for the loss from the rivet-holes; unless this consideration was an element in the formula, it must evidently be faulty. He could not implicitly receive the rule, and hoped it would be very rigidly examined, as, unless it was strictly correct, it might prove very mischievous. Practical men, to save themselves trouble, were very willing to adopt a simple rule, if it came to them well recommended to their confidence; and such adoption of an empirical rule was a great impediment to the projecting of any new system, by diverting the attention of practical men, from inquiring into the real action of the

# TUBULAR GIRDER BRIDGES.

forces, under different conditions. The paper led to the recommendation of a formula, which was subjected to severe scrutiny, and a more definite definition of its efficiency should be required.

Mr. FARLEY stated, in answer to Mr. Farey's question, that the vertical sides varied in thickness; for the first pier it was  $\frac{1}{4}$  inch thick, then for the next pier it was  $\frac{1}{8}$  inch thick, then for 50 feet it was  $\frac{1}{4}$  inch thick, then for 50 feet it was again  $\frac{1}{8}$  inch thick, and for the next pier it was  $\frac{1}{4}$  inch thick. In plan, for a length of 50 feet the metal of the bottom plates was  $\frac{1}{4}$  inch thick, then for 50 feet it was  $\frac{1}{8}$  inch thick, then for 50 feet it was  $\frac{1}{4}$  inch thick, and for the next 20 feet it was again  $\frac{1}{8}$  inch thick, and for the next 20 feet  $\frac{1}{4}$  inch thick (Figs. 4 and 5). The bottom-plate, 12 inches wide and varying in size of the opening to the piers, in the same manner as the plates, as shown in Fig. 5; but this plate was not at the centre pier, nor above those parts of the bridge on the abutments.

The top plates in the top were  $\frac{1}{4}$  inch in thickness. The angle-irons only were taken into the calculations. The lower angle-irons was riveted to the side plates, and the packing strips were considered to be in tension, as the bottom plates themselves were not strained in the same manner they were. Mr. Farley said, that as the strength of the side plates had not been given separately, he could not give the calculations he had made, that they were distributed uniformly over one opening. He was glad the question of continuous beams was well known to old carpenters, that in two openings, the ultimate strength of a beam stretched over the two spaces, was as 2 to 3, and that result had been in question.

The velocity of trains passing over a bridge, what the effect would be if the bridge was so, in a horizontal bridge; he apprehended less strain would be thrown on the bridge by the descent.

He said, if it had not been for objections made by the Hydrographer, to any obstruction in the channel of the Menai Straits, the Britannia Bridge

Fig. 4.

ELEVATION.

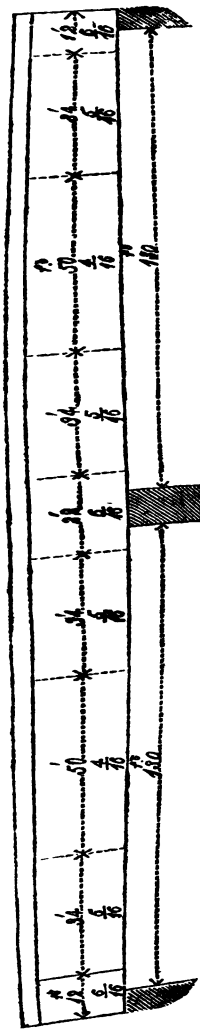
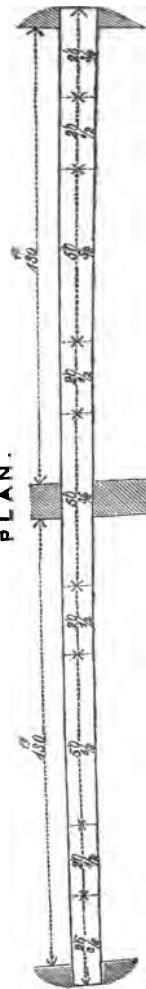


Fig. 5.

PLAN.



Diagrams showing arrangement of Plates in bottom and sides.

would have been erected; and had it not been for inferences drawn from the Report of the Commissioners, and the application to wrought iron, of a formula intended only for cast iron, the Institution would not have had Mr. Fairbairn's paper, nor the interesting discussion which had arisen out of it. It appeared to be considered, that the

contending forces, under different conditions. The paper appeared to be limited to the recommendation of a formula, which certainly should be subjected to severe scrutiny, and a more definite demonstration of its efficiency should be required.

Mr. FOWLER stated, in answer to Mr. Farey's questions, that the metal of the vertical sides varied in thickness; for 22 feet over the central pier it was  $\frac{1}{8}$  inch thick, then for the next 34 feet it was  $\frac{1}{8}$  inch thick, then for 50 feet it was  $\frac{1}{8}$  inch thick, then for the next 34 feet it was again  $\frac{1}{8}$  inch thick, and for the next 12 feet it was  $\frac{1}{8}$  inch thick. In plan, for a length of 50 feet over the central pier, the metal of the bottom plates was  $\frac{1}{8}$  inch thick, then for 20 feet it was  $\frac{1}{8}$  inch thick, then for 50 feet it was  $\frac{1}{8}$  inch thick, then for the next 20 feet it was again  $\frac{1}{8}$  inch thick, and then for the next 26 feet  $\frac{1}{8}$  inch thick (Figs. 4 and 5). There was an additional bottom-plate, 12 inches wide and varying in thickness from the centre of the opening to the piers, in the same proportion as the bottom-plates, as shown in Fig. 5; but this plate did not extend over the centre pier, nor above those parts of the girder which rested upon the abutments.

The vertical plates in the top were  $\frac{1}{8}$  inch in thickness throughout. Nine angle-irons only were taken into the calculation, as one-half of the two lower angle-irons was riveted to the sides. In the calculations, the packing strips were considered to be in as good a position, to resist tension, as the bottom plates themselves, but as the angle-irons were not strained in the same manner they were omitted.

Mr. COLTHURST said, that as the strength of the sides of the main girders had not been given separately, he could state as a result of some calculations he had made, that they were equal to a strain of 270 tons, distributed uniformly over one opening.

Mr. GLYNN was glad the question of continuous beams had been brought forward: it was well known to old carpenters, that if two joists spanned over two openings, the ultimate strength was not so great as when one joist stretched over the two spaces, in fact the difference of strength was as 2 to 3, and that result had been shown to obtain in the bridge in question.

With respect to the velocity of trains passing over a bridge, it ought to be borne in mind, what the effect would be if the velocity was infinite, or nearly so, in a horizontal bridge; he apprehended, that in such a case, a less strain would be thrown on the bridge than if the weight was quiescent.

Mr. WALKER said, if it had not been for objections made by the Admiralty and their Hydrographer, to any obstruction in the way of the navigation of the Menai Straits, the Britannia Bridge never

With regard to the continuity, he had ascertained, from his own calculations, that the deflexion of a simple girder, of that span, without continuity, would be 2 inches; whereas the result of the experiments had shown the actual deflexion to be  $1\frac{1}{2}$  inch, and he was prepared to show, that the strain did not amount to 5 tons on the square inch of section.

He had also directed attention to the vague feeling which existed, that the movement of a train over a tubular bridge, imparted a great strain to the bridge, by impact, or concussion; that point might henceforth be dismissed from their consideration; no one had ventured to offer an opinion, that it had the slightest practical effect, on beams of that extent. Before such a girder could be injured, the rails on which the train travelled must be crushed, or broken, and he believed, that the rails throughout the kingdom were daily and hourly submitted to a much greater strain.

The case then resolved itself into the simple question, Why was the Torksey bridge rejected, and what evidence had been given to justify such a step? Captain Simmons had Mr. Fairbairn's paper before him, and might have explained why he had not even acted on the suggestions contained in it. He thought the time had arrived, when they were entitled to know the real grounds on which the public had been deprived of the convenience of the railway, and the Company had been subjected to the loss they must have sustained by its being kept closed.

Mr. C. MANBY, *Secretary*, said, he was instructed by Mr. Fairbairn, to express his regret at not being able to be present at the discussion of the paper, which had been prepared for the double purpose of affording information to the Railway Commissioners, and for raising a discussion before the Institution. He had approached the inquiry without any partizan feeling, and had endeavoured to bring forward only practical facts. He was directly opposed to unnecessary interference with the professional responsibility of either civil, or mechanical engineers, and in this, as in all similar cases, he thought it better, that the opinions entertained should be embodied in a paper, and be submitted to the tribunal of the Institution, where they would receive fair and candid consideration. In revising his first views, he had deemed it expedient to modify his proposition for the proportion of the depth of the girder, to the span, and had now concluded that it was preferable to reduce the depth for the larger spans.

He thought the reasons were satisfactory, for not taking into account the continuity of the girder, when calculating the ultimate strength; he was aware of the difference of opinion on that point,

#### TUBULAR GIRDER BRIDGES.

ure was to be measured by the amount not gathered, from anything that had practically any important effect in a structure constructed of materials possessing such properties as to exert the utmost tensile strength. He replied, that the point raised by him in the present state of knowledge, he was not sure the Commissioners had intended to have tried at that point, in order to ascertain what amount of strain was exhibited, before the breaking point of wrought iron, as well as the effect of impact, and the time had expired, and their money was exhausted, so that the subject could be investigated.

Mr. Fairbairn denied that he had made use of the formula for cast iron. When he reported on the subject, he took into account the area of a wrought-iron girder; but he certainly did not take into account the fact of its being a continuous beam. He was in agreement with Mr. Scott Russell in the practice of using a continuous beam, because he believed the beam in question was required to support the central pier, as to support all the weight brought upon it, and therefore he thought the objection had been read, however interesting, did not require a discussion. He could not subscribe to Mr. Russell's statement that the strain brought on the bridge would be excessive, because he could not admit the extent endeavoured to be shown by the results that had been exhibited.

Mr. Fairbairn said, his remarks at the commencement of the discussion on the objection he felt to the application of the formula, laid down by Mr. Fairbairn, and his exception, that formula had been conceived, that it did not take into account several elements which ought to be regarded in the consideration of tubular bridges; it did not notice the effect of the quantity of metal in the sides of the tubular girders, or the material omissions, in a paper which proposed the proportions of tubular girders. When Mr. Russell calculated, that one-third of the strength of the Yorksey bridge was derived from the ends, he must contend, that a case had been made out for the formula, which omitted that element from the calculation, imperfect, and was not to be relied on.

With regard to the continuity, he had ascertained, from his own calculations, that the deflexion of a simple girder, of that span, without continuity, would be 2 inches; whereas the result of the experiments had shown the actual deflexion to be  $1\frac{1}{2}$  inch, and he was prepared to show, that the strain did not amount to 5 tons on the square inch of section.

He had also directed attention to the vague feeling which existed, that the movement of a train over a tubular bridge, imparted a great strain to the bridge, by impact, or concussion; that point might henceforth be dismissed from their consideration; no one had ventured to offer an opinion, that it had the slightest practical effect, on beams of that extent. Before such a girder could be injured, the rails on which the train travelled must be crushed, or broken, and he believed, that the rails throughout the kingdom were daily and hourly submitted to a much greater strain.

The case then resolved itself into the simple question, Why was the Torksey bridge rejected, and what evidence had been given to justify such a step? Captain Simmons had Mr. Fairbairn's paper before him, and might have explained why he had not even acted on the suggestions contained in it. He thought the time had arrived, when they were entitled to know the real grounds on which the public had been deprived of the convenience of the railway, and the Company had been subjected to the loss they must have sustained by its being kept closed.

Mr. C. MANBY, *Secretary*, said, he was instructed by Mr. Fairbairn, to express his regret at not being able to be present at the discussion of the paper, which had been prepared for the double purpose of affording information to the Railway Commissioners, and for raising a discussion before the Institution. He had approached the inquiry without any partizan feeling, and had endeavoured to bring forward only practical facts. He was directly opposed to unnecessary interference with the professional responsibility of either civil, or mechanical engineers, and in this, as in all similar cases, he thought it better, that the opinions entertained should be embodied in a paper, and be submitted to the tribunal of the Institution, where they would receive fair and candid consideration. In revising his first views, he had deemed it expedient to modify his proposition for the proportion of the depth of the girder, to the span, and had now concluded that it was preferable to reduce the depth for the larger spans.

He thought the reasons were satisfactory, for not taking into account the continuity of the girder, when calculating the ultimate strength; he was aware of the difference of opinion on that point,

#### TUBULAR GIRDER BRIDGES.

fer to disregard that element, as he has per (page 6).

be distinctly understood, that he had not attempted to assign empirical rules for the design, but was anxious to submit his views and calculations for the careful consideration of the authorities, and to have the subject fairly discussed. He was confident in the accuracy of the formula, and had been confirmed in his opinion by some of the first mathematicians. He had found that the formula had afforded the most satisfactory results, and he found its efficiency perfectly consistent with application; nevertheless he was quite willing to be most happy to receive a better opinion, and he must still adhere to that which he considered correct; and as nearly all the tubular bridges erected, had been constructed according to his plan, and proved successful, he contended it would not be until a better could be substituted for it.

To complete the narrative of the events connected with the construction of the Torksey bridge, it is necessary to give extracts from the reports of the Inspecting Officers to the Commissioners, and from the correspondence between the Board and the Board of Railways on which the bridge in question is situated. On December 24, 1849, Captain Simmons reported to the Board that he had examined the girders by bringing on to the two lines of the bridge, with their tenders, weighing together, and found that each beam, or tube, was found to be strong enough to appear to possess sufficient strength to support the weight it might come upon them in practice. The construction was not accurate line, nor were they very accurate in the rivets appeared to be not very perfect. He anticipated under such a load, that the construction of the bridge, the superstructure, was only about 180 tons, and that the weight of the bridge in the event of two trains passing each other, was a large proportion to the permanent weight of the bridge; and considering also the amount of weight it would bear, he did not feel sufficient confidence to recommend the Commissioners to authorize the bridge for the conveyance of the public, until it was stiffened.

Captain Simmons, dated January 2nd, 1850.

Fowler directed his attention to an error in his calculations, arising from his having assumed 80 tons as the weight of the four engines and tenders, whereas their actual weight was 148 tons. Applying this latter weight, it was submitted, that the bridge was abundantly strong, and that the deflection was less by one quarter of an inch, than might have been anticipated.

To this, Captain Simmons replied, January 5, 1850, that making full allowance for the error into which he appeared to have fallen respecting the weights of the engines, he still maintained the opinion, that the tubes were not sufficient to maintain continuously, for a long period, the strains to which they might be subjected, so long as they were used according to the present construction of the bridge.

In a report to the Commissioners under the same date, Captain Simmons reiterated his former opinion, and stated that the conclusions at which he had before arrived, still remained unshaken, and that he could not report that the opening of the railway for the conveyance of the public would be unattended with danger.

On the 7th of January, Mr. Fowler requested that the bridge might be subjected to a more severe test, suggesting that 250 tons should be placed upon each opening; and he further had no hesitation in asserting, that the Torksey bridge was a stronger and better structure than any tubular girder bridge yet erected by him, and he believed he had constructed a greater number of large wrought-iron tubular girder bridges than any other engineer, and none of them had exhibited the slightest symptoms of weakness, or inefficiency.

This further trial was ordered to be made, and on the 21st January, Captain Simmons reported, that on the 11th January, he had applied the following tests:—

“Three engines, the weights of which were given to me by the locomotive superintendent as together amounting to 108·075 tons, when fully loaded, were placed upon the south road, and produced a deflection of the south beam of ·6 of an inch, and of the north beam, of ·36 of an inch.

“Three more engines, together weighing with their loads, 114·6125 tons, were then placed upon the north road, which increased the deflection of the south beam to 1·20 inch, and of the north beam to 1·32 inch. These deflections were entirely due to the temporary load, and therefore in addition to the permanent deflection due to the constant load, and corresponded as closely as could be expected with the result, which was to be anticipated, from the calculations I had made from the drawings and dimensions furnished to me by the engineer, which gave a deflection of 1·41 inch

for an evenly distributed load over the whole bridge of 222·6875 tons, which was the stated weight of the six loaded engines."

This he considered as a verification of the former calculations, and therefore he remained of the same opinion as to the danger to be apprehended from the use of the bridge.

The opening of the line was therefore further postponed, by order of the Commissioners, for one month from the 22nd January.

Mr. Fowler then made application for a copy of the instructions under which the inspecting officers acted, as their practice appeared to have been recently changed.

On the 25th January, Mr. Fowler requested to be informed by Captain Harness what amount of deflection in the girders of the bridge under a weight of 222 tons would indicate sufficient strength. At the same time, he directed the attention of the Commissioners to the difference of opinion, entertained by engineers, as to the meaning of the paragraph in the Report of the Iron Commission,\* which was understood to be the basis of the rule of calculation, followed by the inspecting officers. It was believed, that the Iron Commission did not intend to give any opinion on wrought-iron girders, and that the multiple of 6 for cast-iron, was only that the ordinary passing load should not exceed one-sixth of the breaking weight. It was premised, that Captain Simmons used the multiple of 6 as between the sum of the girders and roadway, and the greatest passing load and the breaking weight; also that three times the girders and six times the greatest load would be sufficient.

Mr. Fowler then furnished the Railway Commissioners with the opinions of several eminent engineers, in favour of the sufficiency of the bridge, and proposed to meet the objections of the Commissioners, by such an arrangement of the top planking of the platform, as should preclude the possibility of a greater thickness than two inches of ballast, ever being superposed.

On the 21st of February, the Commissioners ordered a further postponement of the opening of the line for one month, in consequence of another report by Captain Simmons (dated February 20th), in which, after explaining to the Commissioners, that he had given the matter his most earnest consideration,—had consulted

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\* "That, as it has been shown that to resist the effects of reiterated flexure iron should scarcely be allowed to suffer a deflection equal to one-third of its ultimate deflection, and since the deflection produced by a given load is increased by the effects of percussion, it is advisable that the greatest load in railway bridges should in no case exceed one-sixth of the weight which would break the beam when laid on at rest in the centre."—*Vide* Report of the Iron Commission, page xviii.

eminent authorities, and had taken steps to obtain the details of such bridges, of similar construction, as appeared likely to afford information as to the effect of time and continuous use upon such structures, he proceeds to reply seriatim to the questions contained in the instructions of the Commissioners, and states:—"In reply to the question, 'whether, if I still remain of opinion, that this viaduct cannot be opened with safety to the public, what further strengthening will be necessary,' I have to state, that for reasons before adduced, I do not consider, that the viaduct can be opened for the continuous passage of trains, with safety to the public, and that it will not be in a condition to be opened, until it shall have been so strengthened, that a load of about 400 tons, (including the weight of the beams themselves, and all the standing parts of the bridge) distributed equally over the platform of one span, shall not produce a greater pressure upon the top plate of the girders than five tons per square inch. In stating this, I have taken what I conceive should be the utmost limit of strains, to which the bridge should be subjected by the given load, considering its nature, nearly 200 tons being made up of railway trains in motion, and the doubtful workmanship in the structure.

"In arriving at this conclusion, I express my opinion with all diffidence, as there is no decided authority upon the subject, and the peculiar circumstances of construction of most bridges very considerably preventing the application of an universal law. Mr. Hodgkinson, whose authority in these matters is entitled to great deference, states, that he conceives that eight tons per square inch is the greatest compressible strain to which a tube of this sort should be subjected; and again, in speaking of the Conway bridge, he states, that a tube of given dimensions, 'if made without joints and loaded without vibration, would bear a weight in the middle of top) without entirely destroying the utility of the material; but plates united by riveting in the best manner in common use, are weaker than plates without joints, in the ratio of three to two nearly; we ought therefore to reduce the computed weight in that ratio, or even greater, since the computation is made on the supposition of the tube being without joints and loaded without vibration.' And again, in commenting on an experiment made upon a large tube forty-seven feet long and about six and a half tons weight, built up of plates three-quarters of an inch thick, being thicker, in fact, than the chief part of the plates in the Torksey bridge, he states, that 'long-continued impact producing a deflection of less than one-

#### TUBULAR GIRDER BRIDGES.

d be required to injure the tube by pressure, & active to the riveting.' sight of the Menai and Conway bridges in prospect, producing vibration (about 1 to 4.5 in) to obviate this danger; but it appears a question of advance should be made for this effect, when the variable and permanent load are altered, and, become nearly equal to one another. The dead rolling load, stated to be 222 tons, which I saw, considerably exceeds one-fifth of the ultimate load the tube may be expected to bear, and it is to be noted that this deflection is in addition to the constant eye load.

Mr. Fowler, in his letter forwarded by Mr. Fowler, states that he has in his own possession, on the force of tubular bridges, and on heavy weights passing, appear to confirm the fact, that the deflection in result due to the height through which the body falls, the deflection is the same at all velocities. To a great extent, with Mr. Fairbairn, that the increase in velocity is not, practically speaking, in most cases apparent. In the present instance it would scarcely be true. Nevertheless, I cannot go so far as to attach no value to impact, by Mr. Hodgkinson, before given, is again aggravated by the concussions caused by motion of the moving weight.

Another remark, that in this question, much must depend on the riveting; where machines are used for the result may be expected than when it is done by the weight of hammer used, or force of blow. The weight of rivet-heads, will make a material difference. In consequence of having seen several split rivet-heads, I am of opinion that the workmanship is defective.

Mr. Fowler, by stating, that he had again inspected the bridge, and had been made to its strength,—that he had no objection with reference to their workmanship, and found no fault in the expression of a want of confidence in the joints was certainly very imperfect, and the joints were not very judiciously made, and the top of the girders was out of line, both horizontally and vertically. In my opinion the opening of the line would be attended by reason of the insufficiency of the work."

Mr. Fowler then pointed out, that Captain Simmons had evidently neglected the increase of strength due to the continuity of the tubes over the centre pier.

Captain Laffan was then instructed to examine the bridge, and the result was, that on the 18th of March the opening of the line was further postponed for one month.

In the report, dated March 16th, Captain Laffan stated, that the bridge remained precisely in the same condition as when it was inspected by Captain Simmons, on which occasion he decided, that the wrought-iron girders were not sufficiently strong to insure the safety of public traffic. After a careful inspection of the structure, Captain Laffan entirely concurred with Captain Simmons in his opinion, and further "that the opening of the line would be attended with danger to the public, by reason of the insufficiency of the works."

On the 20th of March, Mr. Fowler addressed a letter to the Commissioners, in which, after remonstrating on the shortness of the notice of the intended visits of the Inspecting Officers, which had precluded the possibility of his being present at the inspection of the works,—he examined and commented on the report of February 20th, by Captain Simmons, protesting against the conclusion, that five tons per square inch was the greatest strain to which the metal in the bridge might be safely subjected, inasmuch as Mr. Eaton Hodgkinson's experiments showed, that a compressive strain of eight tons per square inch was perfectly safe.

He also protested against the objection to the workmanship, which although not of the finest and most finished class, was nevertheless perfectly sound, and, for all practical purposes, as good as possible; the slight deflection of 1.26 inch under a weight of 222 tons as stated by Captain Simmons, appearing conclusive against any charge of imperfect workmanship. Mr. Fowler therefore concluded, that there was not any sufficient reason for fixing upon five tons, as the greatest strain to which the bridge could be safely subjected, when no good authority had even suggested a strain of less than eight tons as being perfectly safe.

Assuming, however, that Captain Simmons was justified in his extraordinary requirements for the bridge, Mr. Fowler contended that without any alteration, it actually did comply with those stringent requirements.

In the paper on Tubular Girder Bridges, alluded to by Captain Simmons, Mr. Fairbairn gave a table of fixed proportions, recommended by him, but which were adapted for simple girders over one opening, and in applying his own rule to this case, Mr. Fairbairn

arrived at the conclusion, that although the Torksey bridge did not come up to his standard, the dimensions "were nevertheless sufficient to render the bridge perfectly secure." This conclusion had been arrived at, by treating the bridge as composed of separate and distinct girders; but if Mr. Fairbairn had ascertained the value of the continuity over the centre pier, he would have perceived the enormous additional strength thus imparted to the structure, and that it was fully equal even to the requirements of his own assumed standard.

The condemnation of the bridge by the Inspecting Officers, could only be accounted for, by supposing that they had overlooked, or failed to appreciate, the value of the continuity of the girders, which Mr. Fowler had ascertained, by experiment and by calculation, did actually impart additional strength to the bridge in the proportion of 9 to 14, and a reduction of the compressive strain upon the top plates to 4·60 tons per square inch.

Under these circumstances, Mr. Fowler felt "it impossible to recommend the Railway Company to make any addition whatever to the strength of the Torksey bridge."

At the meeting of the Institution of Civil Engineers on the 26th of March, the increase of strength due to the continuity of the girder over the centre pier, was fully demonstrated;\* but in order to induce conviction on the minds of the Commissioners, it was resolved further to test the results of the theoretical investigations, by experiments conducted on a large scale, and under the actual circumstances of the case. For this purpose Mr. Fowler obtained the assistance of Mr. Pole and Mr. C. H. Wild; and proceeded with them to make a series of experiments on the bridge. These were tried on the 28th of March, 1850, in the presence and with the aid of Captain Simmons and Captain Laffan, and were of the following nature.

The bridge was loaded with ascertained weights, applied in different ways, and the deflection of the northern girder† was taken in various parts of its length, before, during, and after, the application of each load. It was not thought necessary to observe the southern girder also. The manner of taking the deflection was by observations with a level, this being considered more convenient and satisfactory, than by means of a stretched wire. For this purpose a level was firmly fixed on the western pier of the north girder (corresponding with the point A on figure 3), and the horizontal wire of the telescope adjusted to a horizon mark on the eastern pier (C, fig. 3). When, therefore, the deflections were to be taken, a staff, graduated with inches and tenths, was held at various points on the top of the girder,

\* *Vide ante*, page 23 et seq.

† The line of railway at this point runs nearly East and West.

in the line of sight of the telescope, and the reading of the horizontal wire upon the staff noted down. The difference between any two readings for the same point of the girder, under different loads, showed the amount of alteration of level, or deflection, at that point.

In this manner the following trials were made; the observations being taken in each case at points 10 feet apart, as stated in the table of results given hereafter.

1. A series of readings was first taken with the bridge unloaded, *i. e.* the girders sustaining the weight of the structure only. This weight was estimated, by a careful calculation, to be about 145 tons, or  $72\frac{1}{2}$  tons on each girder.\*

2. Nine waggons, loaded so as to weigh 16 tons each, total 144 tons, were distributed over the western opening of the bridge (A B, fig. 3), and readings were taken again, at the same points as before.

3. This load was removed, and readings were taken again with the bridge unloaded.

4. The same load as in No. 2, was distributed over the eastern opening (B C, fig. 3), and readings were taken.

5. The load was removed, and the readings were again taken with the unloaded bridge.

The above readings, being recorded at the time by several parties, were subsequently reduced and compared as follows :—

The mean of the readings, Nos. 1, 3, and 5, which did not differ much from each other, was taken to represent the position of the bridge unloaded, the girders sustaining only the weight of the structure.

By comparison of this with the readings of No. 2. and No. 4, the effect of the load was seen, according as it was applied on the western, or the eastern bay.

The mean of these two results, therefore, expressed the deflection due to the load, as determined by actual experiment.

Finally, it was desirable to ascertain how far this practical result corroborated the theoretical deductions which had been made with respect to the bridge, and the effect of the continuity of its structure. For this purpose the deflection was computed according to the formulæ given in page 32 (Equation III.), and in the same manner as in the table, page 36; but using the altered data of the weight of the structure, and of the load applied.

The comparison of the computed and experimental results is given in the following table :—

\* In the previous experiments this weight was assumed to be 164 tons, but about 20 tons of ballast had been removed, before the last trial.

# TUBULAR GIRDER BRIDGES.

of the TORKSEY BRIDGE.—Comparison of the Calculated and Actual Deflection, as obtained by Experiment, 28th March, 1880.

Distance from End.		Calculated Deflection due to Load.	Actual Deflection.	Difference.
		Inches.	Inches.	Inches.
LOADED OPENING. (Load 144 Tons weight of structure).	End Pier 0 feet.	0·00	0·00	0·00
	5	+0·09	+0·11	0·02
	15	0·26	0·27	0·01
	25	0·42	0·55	0·13
	35	0·52	0·56	0·04
	45	0·61	0·73	0·12
	55	0·66	0·72	0·06
	65	0·64	0·66	0·02
	75	0·61	0·64	0·03
	85	0·55	0·56	0·01
	95	0·45	0·50	0·05
	105	0·32	0·40	0·08*
	115	0·19	0·29	0·10*
	125	+0·05	+0·19	0·14*
	Centre Pier 130	0·00	0·00	0·00
	125	-0·06	-0·02	0·04*
	115	-0·15	-0·06	0·09*
UNLOADED OPENING. (Weight of structure only = 145 Tons).	105	-0·22	-0·15	0·07*
	95	-0·27	-0·23	0·04
	85	-0·29	-0·25	0·04
	75	-0·30	-0·27	0·03
	65	-0·30	-0·20	0·10
	55	-0·27	-0·22	0·05
	45	-0·24	-0·16	0·08
	35	-0·19	-0·11	0·08
	25	-0·13	-0·06	0·07
	15	-0·10	-0·05	0·05
	5	-0·03	+0·03	0·06
	End Pier 0	0·00	0·00	0·00

The difference between the calculated and the actual deflection was generally under one-tenth of an inch, a quantity within the range of errors of observation and other causes, and therefore the correspondence between them was very satisfactory.

The following extracts from a report to the Commissioning Officer, give his account of the result of the experiment to test the value of continuity, as applied to the bridge, the ballast was removed from it, so as to leave a weight of which could be estimated with tolerable accuracy. A distributed load of 144·8 tons over each opening, to which a weight of 144 tons, which was placed in succession, the deflections of each tube being measured in experiments, at every five feet of its length. The results very closely corresponded with theory, the greatest deflection

The magnitude of these differences was ascribed to a slight error in the centre supports of the girder.

case exceeding 0·15 of an inch, beyond that deduced by calculation. These experiments were made with great care, and are therefore to be fully relied on; Mr. Fowler, assisted by Messrs. Wild and Pole, having afforded every possible facility and assistance in rendering them trustworthy. Considering, therefore, the continuity of the bridge as a fully-established fact, it remains to be considered what is the greatest strain that may be brought upon any part of it in practice; and here applying the calculation submitted to the Institution of Civil Engineers in an able paper by Mr. Pole, and supposing both spans to be equally loaded with 400 tons, as stated in my former report, I find that the compression on the top plate at the point of greatest strain is 4·25 tons, and the tension on the bottom 3·91 tons per square inch; I find also that the tension on the top plate over the centre pier is 7·18 tons, and the compression on the bottom the same, these results being calculated under the supposition that the whole sectional area of the top, including plates and angle irons, is effective without any deduction for the 'diminished strength of plates joined by single rows of rivets as before described.' But in order that there may be no question as to the amount of load, it will be well to submit for the consideration of the Commissioners, similar results obtained with weights, concerning which no question can arise, as they can be made of loads in use at the present day upon railways in the kingdom, and may therefore reasonably be expected in the course of the public traffic to come upon this bridge.

“ Weight of permanent load as reduced by Mr.

Fowler with two inches of ballast	. . .	164·8 tons.
Load taken as equally distributed at $\frac{3}{4}$ ton per foot	173	„
Total	. . .	—337·3 tons.

“ With a load of this weight upon each span, the tensile strain per square inch upon the top, and also of compression on the bottom plate of the tube over the centre pier, will be 6·06 tons; and in the case of only one train, of the weight of two-thirds of a ton per foot passing over both openings of the bridge, in consequence of the position, between the tubes, of the rails, about three-fourths of the weight of the train is carried by the tube adjoining it. The tensile strain upon the top, and compression on the bottom, will therefore amount to 5·22 tons per square inch, still exceeding the amount specified in my former report as a maximum.

“ In these results, no allowance has been made for the strength of the top plate being diminished by riveting, so that it does not exceed two-thirds of its original dimensions when submitted to a tensile strain, nor of the form of the bottom, which does not correspond with that of those parts of such wrought-iron structures as

## TUBULAR GIRDER BRIDGES.

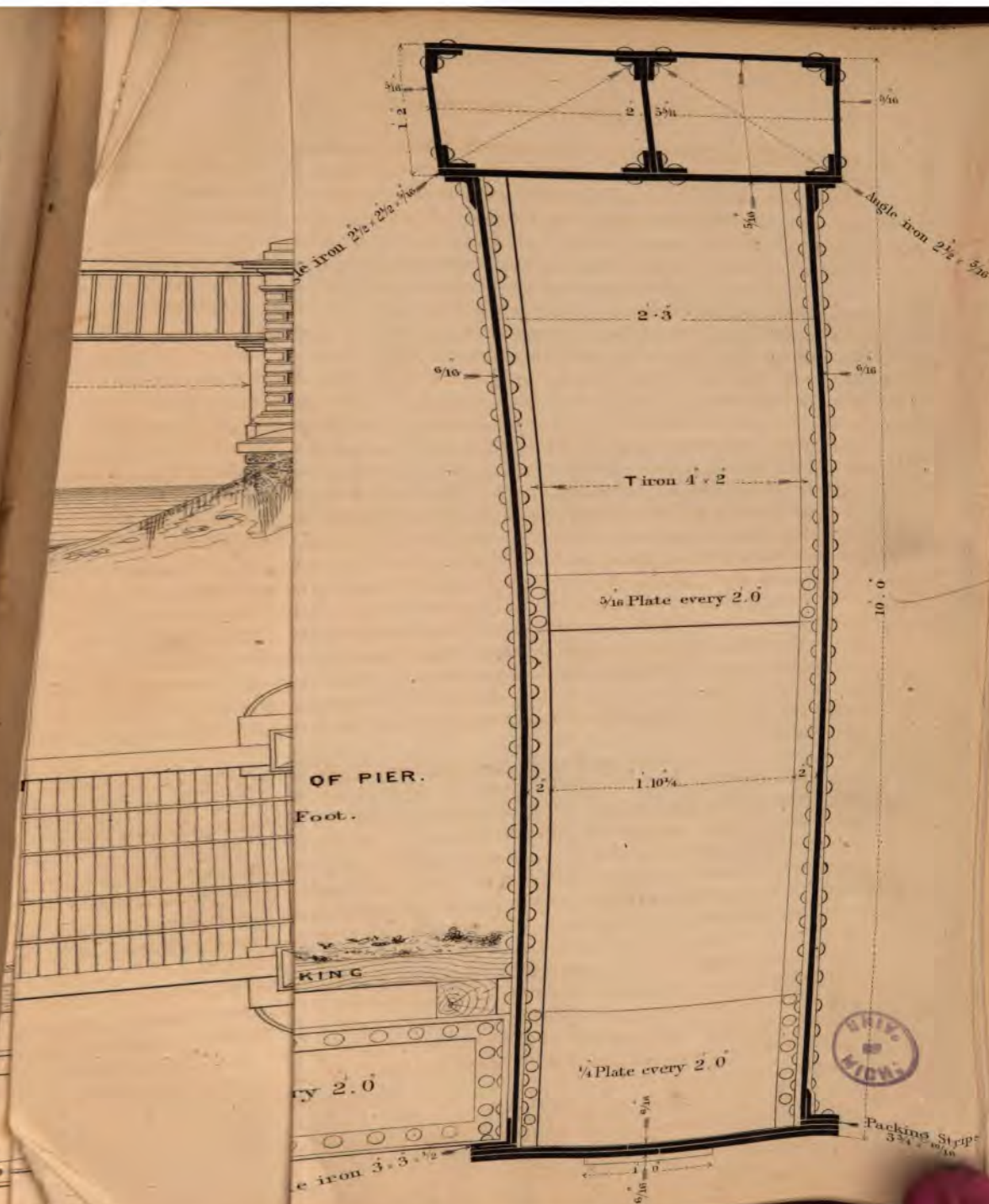
heretofore erected, and are subjected to compression, however, that these heavy strains are upon each arch receives direct support from the masonry below, though the elasticity of those points should be considered. The continuity of the tubes, would, nevertheless, as I have said, if the metal was not altogether destroyed, tend to distribute the strains upon the tubes between the supports, I am therefore of opinion that the Company be permitted to use this bridge, provided their engineer will make such an arrangement on the platform, that the ballast cannot be allowed to settle to a depth of two inches, upon which consideration of the weight of the structure, and also the wear of the tubes, should be applied from time to time, with occasional inspection by an officer of this department, who would report weekly on the amount of traffic, the elasticity of the metal giving the assurance that the bridge over the two spans remain unimpaired. On the 6th of April the Commissioners informed the Secretary of the Lancashire, Sheffield, and Lincolnshire Railway Company that they had reconsidered the question of the propriety of allowing the bridge to be opened, and having received a further report on the state of the Arksey bridge, they were willing to allow it to be used, on being informed that the recommendations as to the ballast had been complied with, and on receiving an assurance from the Company, that should it appear necessary to the Inspecting Officer during the future period, on an examination of the bridge, that it required strengthening, the railway company would promptly attend to the necessary repairs.

In the planking of the platform, limiting the thickness of the ballast to 2 inches, as offered by Mr. Fowler (page 10), was made, and on the 25th of April formal permission was given by the Commissioners for the opening of the line. It is to be regretted that an important line of railway been arbitrarily closed for upwards of four months, and a bridge been condemned, which, when examined by practical engineers, had been proved to be of ample strength, and all this in consequence of the attempt to introduce the system of centralization and of Government supervision, which has been found to be so pernicious in Continental States, and the employment of officers who possessed undoubted skill for their own military duties, but who were placed in a false position where they were entrusted with the execution and control of civil works, and whose previous pursuits precluded their obtaining a practical knowledge of the subject.

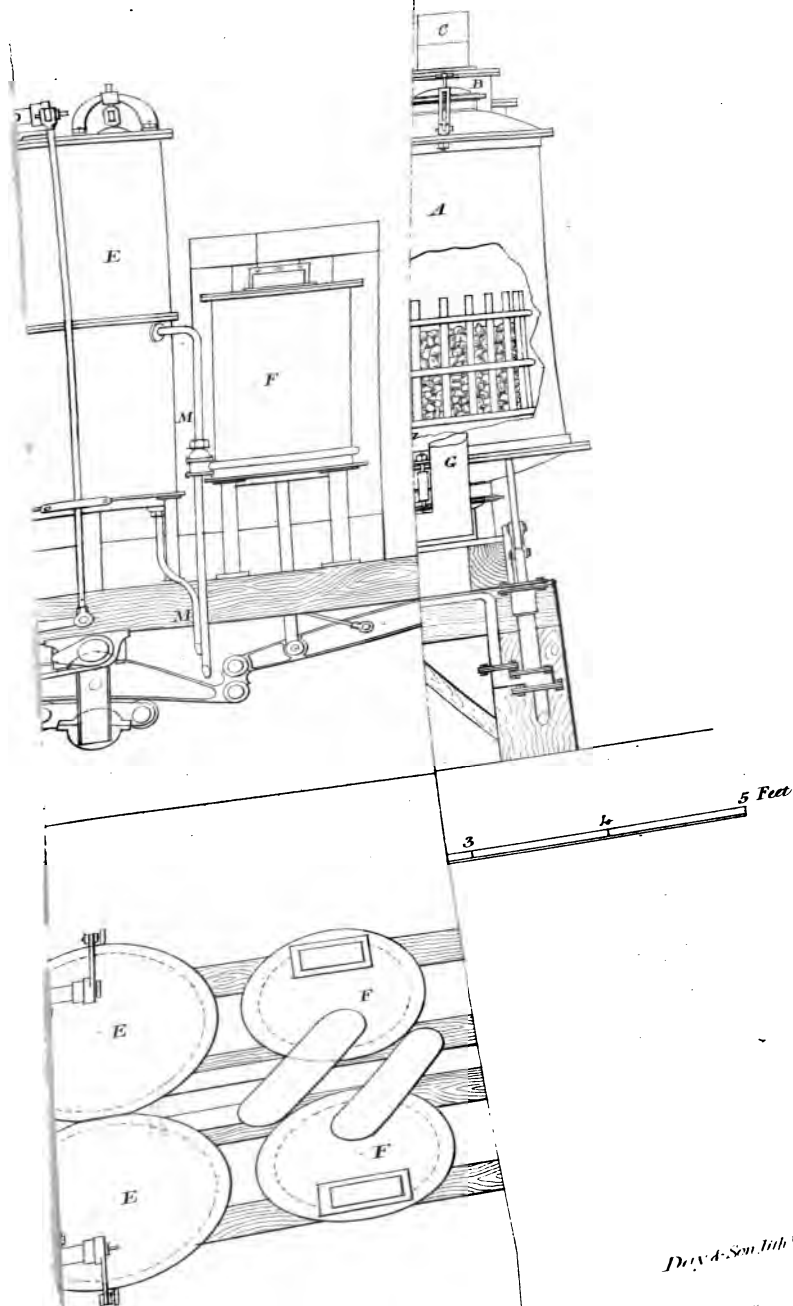
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*Drawn & Sent July 27th to the Queen.*



